

**Content Knowledge for Teaching Science: A Longitudinal Study of Novice Elementary Teachers'
Knowledge Development in a Practice-Based Teacher Education Program and School Contexts**

by

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A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
(Educational Studies)
in the University of Michigan
2019

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Dedication

To Brian, Kora, and Brodie – This is for us. Brian, in all the chaos of life, we continue to succeed and come out smiling. This dissertation is a reminder that no matter the challenge, we will continue to grow together. Kora and Brodie, your genuine love and curiosity for the world is the core of all work in education. I hope this dissertation and all of the love and hard work that went into it reminds you to always ask questions, be inquisitive, and push further. You can achieve anything for the betterment of yourselves and the world around you. Grow, smile, and change the world!

Acknowledgements

I want to acknowledge the many people who helped me complete this dissertation and supported me along the way. First, I would like to thank my advisor and dissertation chair, Betsy Davis, for all of your support during my doctoral career, master's degree, and the years in between. You have guided me throughout my academic career and helped me think more deeply and critically about my work. Betsy, not only do you demonstrate what it means to be a focused, thoughtful scholar, but you also model how to balance the demands of an academic career while being an ever-present mother, daughter, and wife. Thank you, Betsy, for your guidance, care, and genuine image of the possible.

I would also like to thank my committee members for their feedback and encouragement while completing my dissertation. First, I would like to thank Annemarie Palincsar for always pushing me to think more deeply about my work and the contributions it makes to the field. Next, I would like to thank Hyman Bass, not only for your feedback, but also for our many engaging conversations about the work of scientists and mathematicians. I would also like to thank Deborah Ball for your willingness to join my committee further into the work and for continuing to push my thinking about what constitutes knowledge in and for teaching. Lastly, I would like to thank Leah Bricker who provided helpful feedback in the development of my dissertation study and who was always a supportive “cheerleader” throughout my degree.

Conducting education research would not be possible without the wonderful teachers who are brave enough to let us into their classrooms and learn from them. I would like to thank Claudia, Harry, and Diana for their willingness to open up their learning spaces and share what it

means to be a well-started beginning teacher. Not only did they take the time to gather records of their teaching practice, but they also took the time to reflect on their science teaching in ways that displayed the strengths, uncertainties, and mistakes in learning to teach science. As Deborah Ball and her colleagues argue, teaching is unnatural. Claudia, Diana, and Harry were willing to open up that unnatural space (and the challenging feelings that go with it) to support future generations of teachers. Thank you for your willingness, thoughtfulness, and time.

Similar to raising children, completing a doctoral degree takes a village and it is my village that I would like to thank next. Thank you to Ben Tupper, Adam Bennion, Jacquie Handley, and John-Carlos Marino, for your feedback on the many iterations of coding and analyses, as well as your friendship throughout this process. Your time and feedback helped improve both this work and myself as a scholar. Thank you, also, to Gabe Dellavecchia and Katy Easley for being wonderful officemates and thoughtful sounding boards. In support of my writing, I would like to thank Christine Feak and Emily Wilson, for their feedback on the many iterations of this dissertation. Another part of my village are those who have provided emotional support and friendship throughout the process. Thank you to Stacey Brockman, Mollee Shultz, and Emily Wilson for your friendship and support during our many wonderful lunch dates. Lastly, thank you to my many other friends who have been both patient and supportive throughout this process.

The foundation of my village has been my family who have been patient, supportive, and encouraging throughout the many ups and downs of completing a doctoral degree. Thank you to my parents, Kathy and Steve Schultz, who have supported and encouraged me in every aspect of my life, well beyond this doctoral degree. Where I am and who I am today is because of you. Thank you to my other “parents,” Theresa and Jerry Bismack. Your willingness to drop

everything and help with our children or other life situations have been imperative in giving me the time and space to complete my work. Also, thank you to Yiayia and Papou (Kalliope and Bill Drudge) and Grandma and Grandpa (Bunny and Bob Schultz) who were the first teachers in my life. And thank you to my other family members for your patience and support throughout this process.

Lastly, and definitely not least, I would like to thank my husband, Brian, for your support and encouragement while also balancing your own demanding career, long commute, and our active children. Even though you work in a very different field and did not always understand my research, you continued to support me and even gave helpful suggestions on data representations that found their way into this dissertation. There is no way I can thank you enough for all you do in supporting our family and my career. And to our children, Kora and Brodie, thank you for always reminding me – even during difficult times – what matters most. Your smiles, laughs, hugs, kisses, and sincere care and inquisitiveness for all is why I do what I do. You are everything. Thank you. I love you all!

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Abstract

When students engage in the science practices, “they learn that science is not just something that happens in the classroom. It’s actually a process that you can implement in order to solve problems and identify problems... Science is not just knowledge, but it’s action” (Y4 Harry Interview 2). As this novice elementary teacher argues – and as is emphasized in current science education reform documents – engaging students in the science practices is important if students are to develop as scientifically literate citizens. This means teachers, including elementary teachers, need to develop an understanding of the science practices and how to teach them, yet we know little about what elementary teachers know about them or the opportunities supporting knowledge development. Also, few studies investigate how teachers’ knowledge develops over time and what opportunities support that knowledge development. To address these gaps, I ask two overarching research questions: a) *How do novice elementary teachers develop their content knowledge for teaching science over time? And what opportunities support the development of their content knowledge for teaching science over time?*

I used a qualitative, longitudinal, case study approach to investigate three novice elementary teachers’ knowledge development and learning opportunities across four years – two years in a practice-based teacher education program and their first two years teaching. To respond to research question one, I coded and analyzed videorecords, lesson plans, reflections and interviews of the novice elementary teachers’ science teaching. I also analyzed the quality of the teacher’s knowledge of the science practices and how to teach the science practices over time. To respond to research question two, I coded and analyzed course syllabi, assignments,

readings, and PowerPoint slides for three courses foregrounding science teaching, as well as videorecords of class sessions in the Elementary Science Methods course within the practice-based teacher education program. I also coded and analyzed surveys and interviews with the novice elementary teachers, as well as interviews with their mentor teachers and principals within the school contexts.

In their teaching practice, these novice elementary teachers primarily drew on their understanding of the science concepts and practices, as well as their knowledge of how to teach science. These teachers also demonstrated stronger understanding of how to teach the science practices compared to a lesser understanding of what the science practices are. Across the four years, the teachers mainly had opportunities to develop their pedagogical content knowledge with some opportunities in the Elementary Science Methods course supporting their understanding of the science practices. Overall, when supported, these novice elementary teachers were able to develop as well-started beginners who drew on aspects of their content knowledge for teaching science throughout their teaching practice.

To support novice elementary teachers in becoming well-started beginners, learning opportunities should be carefully designed to support teachers' pedagogical content knowledge and understanding of the science practices, because teacher education programs and school contexts likely provide the main opportunities foregrounding these knowledge sub-domains. Also, providing opportunities that help novice elementary teachers develop their knowledge for how to teach science may provide a foundation for elementary teachers to develop as well-started beginning science teachers with further knowledge developing later in their careers. Helping students become scientifically literate citizens means elementary teachers need to develop the necessary content knowledge for teaching science for engaging students in the work of science.

Chapter 1 Introduction

Many pressing social issues, from climate change to fracking to cancer treatments, require citizens to make informed decisions based on a sound understanding of scientific concepts and an ability to discern what counts as appropriate, accurate, and sufficient evidence (National Research Council, 2012). This type of evidence-based evaluation and critique is what scientists and engineers do in their own work. The prevalence of this type of reasoning means students should also engage in these practices if they are to become informed citizens able to make educated decisions.

New science education reform documents (National Research Council, 2012; NGSS Lead States, 2013) aim to prepare students for critically engaging with science-related current events by intentionally integrating science concepts with science practices. This involves integrating three dimensions: disciplinary core ideas, crosscutting concepts, and science practices. Disciplinary core ideas are the science concepts that students learn during their K-12 education (e.g., studying typical weather conditions during different seasons). Crosscutting concepts are constructs, such as energy, that are “common to so many areas of science and engineering” (National Research Council, 2012, p. 85). Science practices highlight the work scientists and engineers engage in by illuminating how scientific knowledge is developed, articulated, and critiqued. Integrating the three dimensions supports students in making sense of natural phenomena.

To emphasize the integration of the dimensions, all three dimensions are combined within a single performance expectation (often referred to as a “standard”). For example, a fifth-grade Earth science performance expectation states, “Represent data in graphical displays to reveal patterns of daily changes in length and direction of shadows, day and night, and the seasonal appearance of some stars in the night sky” (NGSS Lead States, 2013). The science practice in this performance expectation is representing data in graphical displays, the crosscutting concept involves identifying patterns, and the disciplinary core ideas are about shadows, day and night, and seasons. The authors of the NGSS intentionally integrated all three dimensions to “reflect the interconnected nature of science as it is practiced and experienced in the real world” (NGSS Lead States, 2013, Appendix A, p. 1).

In particular, by integrating the science and engineering practices with the disciplinary core ideas and the crosscutting concepts, the focus of learning science is more on understanding how science knowledge is constructed, evaluated, and critiqued. With the accessibility of science information today it is important for students to understand how the science concepts came to be and what it means to critique whether information is reliable and valid. Just knowing about science concepts is not enough to reason through the validity of the concepts and how they relate to everyday issues. By integrating the three dimensions in the NGSS, policymakers, researchers, and educators argue for science learning to be about knowing how science is developed and the validity of science concepts beyond just knowing what the science concepts are and how they relate to one another.

Also, the explicitly integrated approach of the NGSS is different from previous science reform documents that left this type of integration open to interpretation by teachers, administrators, educational researchers, among others (National Research Council, 1996). This

shift is atypical in elementary classrooms (Banilower et al., 2018; Plumley, 2019) and different from how teachers learned science themselves (Lortie, 1975). It necessitates an increase in teachers' knowledge of science to include knowing what and how to engage students in the “doing” of science (science practices) to inform what we know about science (disciplinary core ideas and crosscutting concepts) (Bybee, 2014). We need to better support teachers' understanding of the integration of that “doing” with the “knowing” in science.

Challenges and Gaps with Studying Elementary Teacher Knowledge

Teachers, particularly elementary teachers, tend to not have strong content knowledge (e.g., Abell, 2007; R. D. Anderson & Mitchener, 1994; National Academies of Sciences Engineering and Medicine, 2015; Van Driel, Berry, & Meirink, 2014) and they often hold ideas similar to their students about scientific concepts (Van Driel et al., 2014). A factor influencing their potentially limited knowledge is the broad scope of topics taught in elementary classrooms. These include different subject areas, such as science, mathematics, English language arts, social studies, as well as the disciplines within those subjects. For example, in science alone, an elementary teacher needs to know the substantive scientific ideas (e.g., concepts and theories) and the syntactic knowledge (e.g., understanding of how to analyze data, evaluate evidence, develop and use models) (Schwab, 1962; Shulman, 1986) within physical, life, and earth and space sciences. However, scientific knowledge is not all that teachers are required to know; they also need to know how to engage students in learning science. The knowledge elementary teachers need for productive science teaching is complex and can be challenging to develop due to their limited experiences with deep science learning opportunities.

The study of teacher knowledge has primarily focused on the knowledge of science concepts (Abell, 2007), with limited attention to teachers' syntactic science knowledge (Davis,

Petish, & Smithey, 2006; Lawson, 2002; National Academies of Sciences Engineering and Medicine, 2015). Syntactic science knowledge is similar to the science practices in that it emphasizes *how* science knowledge is constructed (Schwab, 1962). Typically, research on the science practices focuses more on teachers' *abilities* to engage students in these practices (e.g., Crawford, 2000; McNeill & Krajcik, 2008) and less on what teachers *know* about the science practices (e.g., McNeill, González-Howard, Katsh-Singer, & Loper, 2016). Also, teachers' knowledge is often studied using assessments and questionnaires, which is "more or less distant to classroom teaching" (Van Driel et al., 2014, p. 864). In order to adequately support elementary teachers, we need to know what they know about the science practices and how their knowledge influences their teaching practice (Alonzo, Kobarg, & Seidel, 2012; Ball, Thames, & Phelps, 2008; Johnson & Cotterman, 2015; Robertson et al., 2017).

Teaching that foregrounds the science and engineering practices can be more engaging for students and also more representative of the work of scientists and engineers (National Research Council, 2012). It can also encourage teachers to "attend closely to the varied ways in which students argue from evidence or interpret data as a foundation of learning in science, and to build on students' ideas, experiences, and perspectives as a core part of teaching" (Bang, Brown, Calabrese-Barton, Rosebery, & Warren, 2017, p. 33). For elementary teachers who may not have strong knowledge of science concepts (Abell, 2007), teaching science that foregrounds the science and engineering practices may be a way to engage students in reform-oriented science teaching that is potentially more accessible for elementary teachers. Yet, we know little about what elementary teachers know about the science and engineering practices (e.g., Davis et al., 2006; Ricketts, 2014; Zangori & Forbes, 2013). Further research is needed that investigates

elementary teachers' knowledge of science, particularly of the science practices, if they are to successfully support students in becoming scientifically literate citizens.

Defining the Problem

The re-defining of what constitutes science knowledge for teaching (NGSS Lead States, 2013), means there is a need for researchers and teacher educators to understand teachers' knowledge of the disciplinary core ideas, crosscutting concepts, and science practices, as well as their knowledge of how to teach science. Yet, we know little about elementary teachers' knowledge of the science practices, in particular, and how to engage students in them (Davis et al., 2006). By using the content knowledge for teaching framework developed by studying mathematics teachers' knowledge in practice (Ball et al., 2008; Shulman, 1987), we can learn how elementary teachers' knowledge of science and how to engage students in science is evident in their teaching practice.

Supporting elementary teachers' science knowledge and teaching practices involves knowing what opportunities they have to develop their content knowledge for teaching science. Yet, we know little about the opportunities teachers have to develop their knowledge for teaching science (e.g., Appleton, 2002; Arzi & White, 2008). Only when we understand how elementary teachers' content knowledge for science teaching develops over time and how they are supported to develop that knowledge will we be better positioned to support elementary teachers in helping students become scientifically literate citizens.

Research Questions and Study Overview

To address the gaps in the literature, the current study investigated two overarching research questions: *How do novice elementary teachers develop their content knowledge for teaching science over time? And what opportunities support the development of their content*

knowledge for teaching science over time? In the following paragraphs, I further unpack these two overarching research questions into four more specified research questions.

I conducted a longitudinal, qualitative case study (Merriam, 2009; Stake, 2000) comparing and contrasting novice elementary teachers' content knowledge for teaching science. To do so, I followed three novice elementary teachers through their teacher education program and into their first two years of teaching. I also characterized the learning opportunities that support teachers' knowledge development within a practice-based teacher education program and the school contexts in which they taught. The specific research questions for this dissertation study are as follows:

1. *How is novice elementary teachers' content knowledge for teaching science evident in their teaching practice over time?* To study how novice elementary teachers' content knowledge for teaching science appears in practice across time, I drew on Zembal-Saul, Blumenfeld, and Krajcik (2000) cycles of teaching to characterize the teaching practice as teachers' planning, instruction, and reflection. Most research studies on teacher knowledge investigated in-service teachers or preservice teachers in their teacher education programs (Van Driel et al., 2014) with few studies following preservice teachers into their first few years of teaching (Davis, 2008; Mulholland & Wallace, 2005).
2. *What learning opportunities are provided in a practice-based teacher education program to support novice elementary teachers' development of their content knowledge for teaching science?* I drew on a range of program documents and other data sources to characterize the learning opportunities supporting the sub-domains of content knowledge for teaching science.

3. *What learning opportunities do the school contexts provide to support novice elementary teachers' development of their content knowledge for teaching science?* I used a range of data sources to study how the sub-domains of content knowledge for teaching science were supported (or not) by the learning opportunities in the teachers' school contexts where they taught during their first two years of teaching.
4. *How do the learning opportunities in the teacher education program and the school contexts compare to the novice elementary teachers' knowledge evident in their teaching practice?* I compared how the teachers' content knowledge for teaching science related to the learning opportunities supporting their knowledge development. To do so, I created figures representing the trajectories of these teachers' knowledge development and opportunities to learn across the four years. I do not intend to make causal claims as to what the teachers learned from the opportunities.

I used in-depth case studies to explore how teacher knowledge develops over time and the learning opportunities supporting teachers' knowledge development in light of the new reforms in science education. To do so, I analyzed the teachers' records of practice for evidence of their content knowledge for teaching science. I also analyzed the data for how they understood the science practices and how to teach the science practices. Lastly, I analyzed the course documents and data from the school contexts to characterize the opportunities that the novice elementary teachers had to develop their content knowledge for teaching science.

Findings extend and refine the field's understanding of how novice elementary teachers draw on their content knowledge for teaching science during their teaching practice, which has minimally been studied in science education (e.g., Johnson & Cotterman, 2015; Kademian, 2017;

Robertson et al., 2017). For example, the novice elementary teachers in this study drew more on specific aspects of their content knowledge for teaching science compared to other aspects, similar to other studies (e.g., Johnson & Cotterman, 2015). Specifically, their understanding of science and how to teach science was more evident in their teaching practice than other aspects of their content knowledge for teaching science (e.g., understanding of students' ideas, challenges, and backgrounds related to science). I also found that the teachers' understanding of particular dimensions of the science practices may serve as possible "readiness" (Davis & Smithey, 2009; Smithey, 2008) or serve as building blocks for understanding the science practices and how to engage students in them.

The opportunities to learn mainly supported the teachers' knowledge of how to teach science with some opportunities supporting their knowledge of science curriculum, students, and the science practices. Some opportunities supporting their understanding of science teaching led the teachers to pursue opportunities supporting their understanding of science. For example, as the teachers experienced opportunities supporting their understanding of science curriculum, they sought opportunities to further develop their understanding of science concepts. Not only does my dissertation extend the literature on what it means to study opportunities to learn in multiple contexts (teacher education and schools) (e.g., Darling-Hammond, 2006a; Van Driel & Berry, 2017), it also highlights the complexity in teachers' development of their knowledge of science and how to teach science. For example, I found that *learning how to teach science* can lead teachers to pursue opportunities to *learn about science*. Because my dissertation was conducted with three teachers and with a framework rarely used in science education, further work is needed on the interplay of novice elementary teachers' knowledge and how they develop that knowledge in multiple contexts over time.

Chapter 2 outlines literature on the science practices, opportunities to learn in teacher education programs and schools, and teachers' knowledge in science. The chapter ends with my framing of the content knowledge for teaching science framework. Chapter 3 outlines the methods, participants, data sources, and coding and analyses of the data. The data sources included a variety of records of practice from the novice elementary teachers' science teaching, as well as documents from courses and school contexts. Chapters 4, 5, and 6 outline the findings from analyses of the data. Specifically, Chapter 4 characterizes the opportunities to learn that the teachers had for developing their content knowledge for teaching science in their practice-based teacher education program and the school contexts. Chapter 5 characterizes the teachers' knowledge evident in their practice and their understanding of the science practices. Using cases of each teacher, Chapter 6 describes relationships between the opportunities to learn and the teachers' knowledge across the four years. Chapter 7 connects the findings from my dissertation to the literature on opportunities to learn and teachers' knowledge in and for teaching science.

Chapter 2 Literature Review and Theoretical Framework

This chapter outlines the literature grounding my dissertation study and my framing of teacher knowledge in and for teaching science. The following sections describe strengths and challenges when teaching elementary science, as well as the complexity of disciplinary knowledge for teaching elementary science with a focus on teachers' understanding of science concepts and science practices. I review current research on the study of teachers' knowledge in science education and how learning opportunities can support teacher knowledge development. Lastly, I outline my theoretical framework for content knowledge for teaching science (CKT-S), which is my take on elementary science teacher knowledge and how learning opportunities can support knowledge development.

Strengths and Struggles Facing Elementary Science Teachers

For students to become scientifically literate citizens capable of making informed decisions, teachers must design learning environments that center on science concepts and practices, yet there are many obstacles that teachers face when attempting to do so (Davis et al., 2006). For example, elementary science teaching that engages students in the concepts and practices of multiple science disciplines (physics, biology, chemistry, earth and space sciences), tends to differ from how teachers learned science themselves (Lortie, 1975). The fact that standardized testing typically focuses on mathematics and English language arts means science is not frequently taught in elementary classrooms and teachers are given minimal support for their science teaching (Banilower et al., 2018; Marx & Harris, 2006). When science is taught, teachers

tend to focus on students' enjoyment of science (Furtak & Alonzo, 2010; Roth, 2014), instead of scientific sensemaking that integrates the science and engineering practices with the science concepts (Bismack, Arias, Davis, & Palincsar, 2014; Roth, 2014; Roth et al., 2006).

Learning how to teach elementary science can be even more challenging for *novices* due to the need to balance many constraints while also learning the intricacies of elementary teaching (Davis et al., 2006; Davis & Smithey, 2009). Novice elementary teachers tend to have limited science knowledge (Abell, 2007) and knowledge about the nature of science and how scientific knowledge is developed (Davis et al., 2006; National Academies of Sciences Engineering and Medicine, 2015). These challenges lead some novices to avoid teaching science entirely (Appleton, 2003; Davis & Smithey, 2009).

Teaching About Science Concepts and the Science Practices

For teachers to adequately support students in becoming scientifically literate citizens, they need to provide learning opportunities that engage students in science concepts and practices, which means the teachers need to know the concepts and practices (Schwab, 1962; Shulman, 1986). Due to the limited research on teachers' knowledge of the science practices (Davis et al., 2006), the following sections outline current research on teachers' practices for engaging students in the science concepts and practices. When available, I include literature on teachers' knowledge of specific science practices (e.g., Bowen & Roth, 2005; Ricketts, 2014). The purpose is to characterize what is meant by each science practice and what we currently know about how teachers engage students in the science practices. I do not discuss the science practices of mathematical and computational thinking or engineering, because both are rarely taught in elementary classrooms (Plumley, 2019) and were not prominent in the participants' classrooms in this dissertation study.

Asking scientific questions

Asking scientific questions is critical when engaging in scientific thinking and reasoning (National Research Council, 2007, 2012), yet there is limited research on how teachers support students in doing so (Roth, 2014). Often the scientific questions asked in elementary classrooms are teacher-driven and guided by the curriculum, thereby limiting opportunities for students to learn how to ask scientific questions (Biggers, 2017). In contrast, teachers can help students learn to organize and construct their own scientific questions by using heuristics, question starters, and categorizations (Cavagnetto, Hand, & Norton-Meier, 2010; Sharkawy, 2010; Zembal-Saul, Hershberger, & McNeill, 2012). Teachers can also elicit and use students' questions about the natural world as instructional tools for designing class science investigations, thereby emphasizing the importance of questioning in science (Bismack & Haefner, in press; van Zee, Iwasyk, Kurose, Simpson, & Wild, 2001).

Scientific modeling

When students engage in scientific modeling they learn to construct knowledge in ways scientists do (Duschl, 2015; Duschl & Grandy, 2008; National Research Council, 2007; Nersessian, 2008; Schwarz et al., 2009) by “representing patterns in data and formulating general models to explain candidate phenomena” (National Research Council, 2007, p. 258). The practices that scientists and students engage in when constructing scientific models can involve cycles of questioning, constructing, evaluating, revising, and explaining (Lehrer & Schauble, 2006). Implicit in the research of how elementary students construct and reason with models is how teachers support students in constructing and using models (Lehrer & Schauble, 2002, 2012; Roth, 2014).

Teachers can engage in different instructional strategies to guide students in the construction, evaluation, and modification of their scientific models. For example, these can involve providing time and resources, as well as scaffolding for students to help them recognize the qualities in a system that they want to amplify or reduce (Lehrer & Schauble, 2012). It also involves supporting students to use models to construct explanations and arguments about phenomena (Passmore, Schwarz, & Mankowski, 2017; Ricketts, 2014; Schwarz et al., 2009), as well as for generating data (Ricketts, 2014). This can be challenging, because some preservice elementary teachers struggle to understand what constitutes a model (Ricketts, 2014). To understand what models are and how to engage students in developing and using models, though, teachers need extensive support (Windschitl, Thompson, & Braaten, 2008). Scientific modeling is a crucial element of scientific practice due to its interconnectedness with other science practices (National Research Council, 2007; Osborne, 2014; Passmore, Gouvea, & Giere, 2014; Roth, 2014).

Planning and carrying out investigations

Similar to scientific modeling, planning and carrying out scientific investigations is a critical science practice that supports scientific sensemaking (Duschl & Bybee, 2014; National Research Council, 2012). Engaging students in planning and carrying out investigations involves the systematic collection of data to be used to construct explanations and arguments (National Research Council, 2012; Windschitl, 2017). To do so, teachers need to provide scaffolding for designing investigations, modeling how to conduct investigations, and providing opportunities for students to collaborate during their investigations (Kademian & Davis, in press; Metz, 2011; Windschitl et al., 2008). When designing investigations, teachers should foreground students' questions (Crawford, 2000; Metz, 2011) and use discourse moves (e.g., asking students open-

ended questions) to elicit those questions (Harris, Phillips, & Penuel, 2012; Kademian & Davis, in press; Windschitl et al., 2008). Because of the many dimensions of having students plan and conduct scientific investigations (Duschl & Bybee, 2014), I expand on the details of this science practice in the following two sections that articulate what it means to engage students in making scientific predictions and observations.

Making scientific predictions. Constructing scientific predictions involves developing a supported idea of what may occur in a scientific investigation. This practice is part of planning and carrying out investigations (Ricketts, 2014) and analyzing and interpreting data and is also important for arguing scientifically (Arias, Smith, Davis, Marino, & Palincsar, 2017). Specifically, scientific argumentation involves “the coordination of evidence and theory to advance an explanation, a model, a *prediction* or an evaluation” (Duschl & Osborne, 2002, p. 55, emphasis added). Students have an easier time constructing claims for scientific predictions (Lee & Butler, 2003), but struggle with justifying those claims (Bismack, Arias, Davis, & Palincsar, 2015; Sandoval, 2003). To help students develop useful scientific predictions teachers can elicit students’ prior knowledge, provide sentence starters, and provide analogies to help students draw on their prior knowledge when constructing scientific predictions (Arias, Bismack, Davis, & Palincsar, 2016; Oh, 2010). In general, teachers struggle to understand why and how to have students justify their ideas when constructing scientific predictions (Arias, Bismack, et al., 2016; McNeill, 2009).

Making and recording scientific observations. Making and recording scientific observations is critical when conducting scientific investigations (Duschl & Bybee, 2014; Windschitl, 2017). And yet, collecting systematic qualitative and quantitative data can be challenging for elementary students (Arias & Davis, 2016; Bismack et al., 2015; Eberbach &

Crowley, 2009), and these challenges affect students' abilities to construct explanations and arguments. Specifically, students struggle to make everyday observations more scientific in nature (Eberbach & Crowley, 2009). To support students, elementary teachers can explicitly articulate the characteristics of quality scientific observations, which include being clear (neat and specific), complete (including all parts of the phenomena being observed), accurate (recording only what is actually viewed), using labels with scientific vocabulary, and objective (not recording inferences) (Arias & Davis, 2016). Supporting students in collecting systematic data means helping them notice relevant information to record (Eberbach & Crowley, 2009). Recorded observations allow students to easily refer to collected data that can be then used as evidence for explanations and arguments.

Analyzing and interpreting data

Once students have collected their data during a scientific investigation, they need to make sense of that data by identifying patterns in the data and giving meaning to those patterns (Rivet & Ingber, 2017). Supporting students to analyze and interpret data is challenging. For example, it involves prompting students to recognize patterns (Arias, 2015; Ricketts, 2014; Rivet & Ingber, 2017; Zangori, Forbes, & Biggers, 2013), to use representations that organize the data, to discuss inconsistencies in the data (Arias & Davis, 2017a; Ricketts, 2014; Rivet & Ingber, 2017), and to come to consensus about interpretations of the data (Ricketts, 2014). Elementary preservice teachers have done this with varying levels of success (Arias & Davis, 2017a). Preservice teachers also tend to struggle with analyzing and interpreting data and graphs themselves (Bowen & Roth, 2005). Further work is needed to understand how teachers make sense of the science practice of analyzing and interpreting data and how to support students in doing this important work.

Constructing explanations and arguments supported by evidence

Constructing scientific explanations and engaging in argument from evidence are related science practices (Berland & McNeill, 2011) and much of the research with elementary teachers engaging students in the practices has addressed aspects of each (Roth, 2014). These science practices help “[students] understand how scientific knowledge is created while also deepening their understandings of science facts, concepts, and theories” (Roth, 2014, p. 376). Preservice elementary teachers tend to view constructing explanations and arguments as useful for answering investigable questions and generating, evaluating, and refining claims (Ricketts, 2014). Extensive research has investigated how teachers (elementary and middle level) engage students in constructing scientific explanations and arguments (e.g., Arias & Davis, 2017a; Beyer & Davis, 2008; Biggers, Forbes, & Zangori, 2013; McNeill, 2009; McNeill & Krajcik, 2008; Zangori et al., 2013) and students’ challenges with this work (e.g., McNeill, 2011; McNeill, Lizotte, Krajcik, & Marx, 2006; Sandoval, 2003).

To productively engage in explanation and argument construction, students need coherent, aligned instruction yet this can be challenging for teachers, particularly novice teachers (Biggers et al., 2013; McNeill, 2009; Zangori et al., 2013). Some instructional strategies for constructing explanations and arguments include prompting students for evidence with their ideas, providing a structure or heuristic for constructing explanations and arguments (Arias & Davis, 2017a; McNeill, 2009; Zembal-Saul et al., 2012), and discussing the purpose for constructing explanations and arguments (McNeill, 2009; Zangori et al., 2013). Once explanations and arguments are constructed, teachers should support students in evaluating and responding to alternative arguments.

Encouraging students to consider alternative claims based on evidence can be challenging for students and teachers, but doing so helps develop an understanding of how science knowledge is constructed (Zemba-Saul, 2009). To support students in considering an alternative argument, a teacher can use an argument structure to scaffold students' thinking about and construction of arguments (Zemba-Saul, 2009; Zemba-Saul et al., 2012). Teachers can also model how to critique arguments and provide space for students to debate and critique one another's arguments from evidence (McNeill, 2011). Engaging students in argumentation is more than construction of an argument, but also involves prioritizing student talk and reasoning over "the correct answer" (Varelas et al., 2008). Guiding students to critique arguments using evidence is important yet challenging for novice elementary teachers to learn how to do (Davis et al., 2006; Zemba-Saul, 2004, 2009) and occurs infrequently in elementary classrooms (e.g., Biggers et al., 2013; Plumley, 2019; Zangori et al., 2013).

Obtaining, evaluating, and communicating information

Obtaining, evaluating, and communicating information is a critical science practice in that it represents how scientists inform and share their work, which is more than half of the work of scientists (National Research Council, 2012; Tenopir & King, 2004). Engaging students in this practice is complex, though, as it requires many facets of engaging with text. One way is to obtain information from a variety of texts (e.g., scientific papers, newspapers, diagrams, videos, photographs, graphs) (National Research Council, 2012; Norris & Phillips, 2003). Doing so can be challenging for students because the academic and technical language of science is unfamiliar to most students (B. A. Brown, 2004). This science practice also requires students to evaluate texts for their credibility and usefulness for the scientific task in which students are engaging (Bricker, Bell, Van Horne, & Clark, 2017). Teachers need to support students in knowing how to

evaluate the credibility of each text gathered (e.g., scientific journal article compared with an online blog) and whether particular texts are more useful for supporting the arguments being made (e.g., using an article from *Scientific American* on the role of buoyancy in ship design compared with a newspaper article reporting the sinking of a local freighter) (Barton, Heidema, & Jordan, 2002). One way to do this can be to have students compare and contrast different texts for their scientific credibility (Bricker et al., 2017). Lastly, this science practice involves having students communicate their science ideas in ways that reflect the ways scientists communicate (National Research Council, 2012). A key part of communicating is considering the audience and the communication medium, which can both be challenging for students (Bricker et al., 2017). Though students often share their ideas during science discussions in elementary classrooms (Plumley, 2019), this is only one form of communication and does not do enough to engage students in the practice of communicating scientific information. To more authentically engage students in this science practice, teachers need to allot time and attention to doing so in their science classrooms (Bricker et al., 2017; National Research Council, 2012).

Science concepts

When students engage in a science practice, they do so in the service of studying a science concept. Developing an understanding of science involves making connections between science concepts, mechanisms, and structures. In the Framework and NGSS, these are referred to as the disciplinary core ideas (within the disciplines of physical sciences; life sciences; earth and space sciences; and engineering, technology, and the applications of science), and the crosscutting concepts (patterns; cause and effect; scale, proportion, and quantity; systems and system models; energy and matter; structure and function; stability and change) (National Research Council, 2012; NGSS Lead States, 2013). In elementary classrooms, the study of the

disciplinary core ideas and the crosscutting concepts tend to occur concurrently. For this reason, I refer to these as science concepts.

The research on students' understandings of science concepts (e.g., Driver, Leach, Millar, & Scott, 1996; Driver, Squires, Rushworth, & Wood-Robinson, 1994) and how students' learning of the concepts progresses over time (e.g., Duncan & Hmelo-Silver, 2009; National Research Council, 2007, 2012; C. L. Smith, Wiser, Anderson, & Krajcik, 2006) has informed the development of the ideas in the Framework and NGSS. Parallel research on teachers' understandings of many science concepts (Abell, 2007) has been conducted for many years, yet little is known about how teachers develop knowledge of science concepts over time and within different educational contexts (Schneider & Plasman, 2011).¹

Knowledge of science concepts and science practices in and for teaching

The NGSS outlines high expectations for students' learning about science concepts and practices, which means elementary teachers need knowledge of these, as well as an understanding of how to craft learning environments that support students' engagement in science. In particular, teachers need knowledge of *each* science concept and practice and knowledge of how to engage students in *each* science concept and practice (Davis & Krajcik, 2005; Gess-Newsome, 2015; Osborne, 2014). As Figure 2-1 demonstrates, knowledge in and for teaching science is quite complex, because teachers need to understand the science concepts and practices and how to teach them. More research is needed to understand elementary teachers' knowledge about the complexities of teaching science. My dissertation begins to fill this gap in the literature by investigating how novice teachers' knowledge of the science concepts and

¹ Because there are many science concepts that teachers are expected to teach in the elementary grades, I do not outline the research for each concept here.

practices are evident in their teaching practice and how they are supported (or not) to develop their knowledge over time. The following section outlines what is meant by teachers' knowledge in and for teaching.

SMK	PCK	SMK	PCK
SCIENTIFIC AND ENGINEERING PRACTICES Asking questions (for science) Developing and using models Planning and carrying out investigations Analyzing and interpreting data Using mathematics and computational thinking Constructing explanations (for science) Engaging in argument from evidence Obtaining, evaluating, and communicating information		SCIENCE CONCEPTS Physical Sciences Life Sciences Earth and Space Sciences Engineering, Technology, and the Applications of Science Patterns Cause and effect: Mechanism and explanation Scale, proportion, and quantity Systems and system models Energy and matter: Flows, cycles, and conservation Structure and function Stability and change	

Figure 2-1. Subject Matter Knowledge (SMK) and Pedagogical Content Knowledge (PCK) for science concepts and science practices (adapted from National Research Council, 2012)

Knowledge In and For Science Teaching

To support students in becoming scientifically literate citizens, it is important to consider teachers' knowledge and teaching practices for elementary science. In defining teaching practice, I draw on Lampert (2010) who views the word “practice” as having different meanings: teaching as a *collection of practices*, practice as *rehearsing for teaching*, and the practice of teaching as

the profession of teaching. First, the collection of practices includes the many ways teachers engage in the “doing” of their work, namely, planning, instruction, and reflection on the work of teaching (Lampert, 2010; Zembal-Saul et al., 2000). Second, in order to productively engage in the collection of practices, teachers must rehearse (another form of practice) the aspects of teaching. One way for novice teachers to rehearse is to try out decomposed aspects of teaching through approximations (Grossman, Compton, et al., 2009) that emphasize learning from experience (Dewey, 1916). Engaging in approximations involves “both the technical and the intellectual” aspects of teaching (Grossman, Hammerness, & McDonald, 2009, p. 275). Rehearsing teaching is more than just “going through the motions,” but requires the application of complex cognitive strategies by novice teachers. Third, the profession of teaching involves “adopting the identity of a teacher, being accepted as a teacher, and taking on the common values, language, and tools of teaching” (Lampert, 2010, p. 29). These tools include the knowledge needed to engage in productive teaching (Ball et al., 2008; Shulman, 1986, 1987).

How knowledge relates to science teaching practice has been explored in only a small number of studies (e.g., Alonzo et al., 2012; Appleton, 2002, 2003; Johnson & Cotterman, 2015; Park, Jang, Chen, & Jung, 2011; Van Driel et al., 2014). Teachers’ limited knowledge has been shown to influence their science teaching practice. For example, in his study investigating secondary biology teachers’ discourse moves, Carlsen (1992) found that teachers with less science knowledge were more likely to limit classroom conversations about the science concepts, spend less time on instruction, stay close to the textbook topics, and resist students’ efforts to shift the discussion. Unlike the less knowledgeable teachers, those with more knowledge use more reform-oriented science instructional moves and their instruction foregrounding science practices positively relates to higher science knowledge for teaching (Park et al., 2011). Similar

to Carlsen (1992), Appleton (2002, 2003) found that elementary teachers with limited science knowledge tend to either not teach science or choose activities that do not promote scientific sensemaking. To address the lack of scientific sensemaking in elementary classrooms, Roth and colleagues (2011) engaged elementary teachers in studying their own teaching practices and found that doing so led to teachers' increased science knowledge and teaching practices. Each of these studies demonstrates the interplay between knowledge and teaching practice, yet more work is needed to understand this interplay. My dissertation begins to extend the literature on how teachers' knowledge is evident in their teaching practice.

Subject Matter Knowledge of Science Teachers

The study of teachers' knowledge has focused on teachers' understanding of science concepts, typically referred to as subject matter knowledge (SMK). Many of the studies used assessments, questionnaires, and interviews to investigate preservice and early in-service teachers' knowledge of particular science concepts (Abell, 2007; Van Driel et al., 2014). Surprisingly, elementary and secondary teachers alike tended to have limited subject matter knowledge and had misconceptions similar to those held by their students (Abell, 2007; Van Driel et al., 2014). Understanding teachers' knowledge about the science concepts is important, yet not a complete picture of what it means to know science in order to teach science. More research is needed to also understand what teachers know about the science practices.

Not only does science teaching involve knowing the concepts, mechanisms, and structures of the disciplines, it also involves knowing how science knowledge is developed (nature of science) and what it means to do science (science practices) (Abell, 2007; Schwab, 1962; Shulman, 1986). Over the years, there has been extensive research on teachers' understanding of the nature of science (e.g., D. Anderson & Clark, 2011; Lederman &

Lederman, 2014), with less research on teachers' knowledge about the science practices or how to engage in science (e.g., Davis et al., 2006).² Further work is needed to understand what teachers know about the science practices, and how teachers' SMK of the science concepts and practices relate to their teaching practice.

Some researchers have investigated how a teacher's SMK influences teaching practice, though the work is still limited (Van Driel et al., 2014). For example, Hashweh (1987) and Carlsen (1992) suggest that secondary teachers' limited SMK relates to their abilities to make instructional decisions, ask productive questions (higher level vs. lower level), and be able to identify student misconceptions. These and other studies demonstrate that teachers' SMK does impact their instructional abilities (Van Driel et al., 2014) yet there is more to knowing how to teach than just knowing about the science concepts (Grossman, 1990). Also, further work is needed to understand how teachers' SMK develops over time (Schneider & Plasman, 2011; Van Driel et al., 2014).

Most studies investigating teachers' SMK are conducted as a one-time interaction with teachers or they follow them across one year (Schneider & Plasman, 2011). As an exception to this more traditional approach, Mulholland and Wallace (2005) followed one elementary teacher for ten years and found that she primarily developed her SMK during her content courses in her undergraduate program with limited development beyond those years. During her teaching, she developed her pedagogical knowledge, which – when combined with her knowledge of the content – led to gains in her pedagogical content knowledge (discussed in the next section). In comparison, after following secondary science teachers for 17 years, Arzi and White (2008)

² To limit the scope of this dissertation, I focus on teachers' understanding of the science concepts and science practices, but not the nature of science.

found that the teachers did develop their SMK over time through their interactions with curriculum materials. The few longitudinal studies on teachers' SMK development limits our abilities to make sense of these differences in findings and more fully understand how teachers' SMK may or may not develop over time. Also, the few studies may have been impacted by the general shift in research on teacher knowledge to focus on teachers' knowledge of how to teach the science concepts, as well as challenges with conducting longitudinal research in general.

Pedagogical Content Knowledge of Science Teachers

As the research on teacher knowledge continued to shift, the notion of teachers' pedagogical content knowledge developed and with it came different conceptualizations of the construct. Shulman (1986) first characterized the notion of pedagogical content knowledge (PCK) as a "particular form of content knowledge that embodies the aspects of content most germane to its teachability" (p. 9). This includes the "ways of representing and formulating the subject that make it comprehensible to others," (e.g., knowing how to ask sensemaking questions when circulating during a science investigation) and knowing what may be easy or challenging for students about the science (Shulman, 1986, p. 9). PCK also includes an understanding of the curriculum and what it means to read and make informed curricular decisions (e.g., M. W. Brown, 2009; Grossman, 1990; Wilson, Shulman, & Richert, 1987).

In science education, there has been extensive research on teachers' PCK with the development of many different frameworks and methods for study (e.g., Appleton, 2002, 2003; Davis & Petish, 2005; Loughran, Mulhall, & Berry, 2004, 2008; Van Driel et al., 2014; Van Driel, de Jong, & Verloop, 2002; Van Driel, Verloop, & de Vos, 1998). For example, Magnusson, Krajcik, and Borko (1999) expanded the work of Shulman (1986, 1987), Grossman (1990), and others to discuss aspects of the dimensions of teachers' PCK such as knowledge of

students' understanding of science to include knowledge of requirements for learning and areas of difficulty related to specific science concepts. Recently, in response to the many constructs of PCK in science education, various science educators gathered to develop a new construct of PCK in science education called the *teacher professional knowledge and skill* (Gess-Newsome, 2015).

The *teacher professional knowledge and skill* (TPK&S) framework differs from other frameworks of PCK in four main ways (Gess-Newsome, 2015). First, it uniquely highlights the importance of teachers' knowledge being topic-specific (e.g., properties of matter) instead of domain-specific (e.g., physics) as was previously articulated over the years. Second, teachers' PCK is moved from being a larger general construct (as in previous research) to being specific to individual teachers and their work in their own classrooms. Third, the framework distinguishes between canonical teacher knowledge (knowledge that many teachers may have about how to engage students in science) and personal teacher knowledge (knowledge that particular teachers have about how to engage students in science) (Gess-Newsome, 2015; P. S. Smith & Banilower, 2015). Lastly, the framework calls attention to teachers' practice by incorporating "skill" within the framework (Gess-Newsome, 2015). The TPK&S framework also has similarities to other representations of PCK. Specifically, it separates the knowledge of assessments, general pedagogy, subject matter, general knowledge of students, and general curricular knowledge from TPK&S.

A challenge with the many PCK frameworks and studies on teachers' PCK is that they tend to be separated from – though related to – subject matter knowledge (e.g., Gess-Newsome, 2015; Grossman, 1990; Magnusson et al., 1999; Shulman, 1986, 1987; Van Driel et al., 1998). Also, the study of SMK and PCK has separately focused on articulating *what* knowledge teachers have (often canonical knowledge) and not *how* the knowledge relates to teaching

practice (Loughran et al., 2004, 2008; Van Driel et al., 2014; Van Driel et al., 1998). In comparison, the content knowledge for teaching framework, discussed next, highlights the intricacies of SMK and PCK, while placing teachers and teaching practice back at the center of the study on teacher knowledge (Ball et al., 2008).

Content Knowledge for Teaching as Used in Science Education

Content knowledge for teaching, developed in mathematics education, highlights the importance of situating the study of teacher knowledge in teaching practice (Ball et al., 2008). In exploring this construct, Ball and Bass (2000, 2003) sought “to develop a practice-based theory of mathematical knowledge as it is entailed by and used in teaching” (Ball et al., 2008, p. 396). In contrast to much of the research that used assessments, surveys, or interviews to study teacher knowledge (e.g., Loughran, Milroy, Berry, Gunstone, & Mulhall, 2001; Van Driel et al., 2014; Van Driel et al., 2002), the study of teachers’ content knowledge for teaching is derived from studying teachers’ actual teaching practice via video records and other records of practice (Ball et al., 2008). Studying teachers’ practice can provide insights into teachers’ knowledge used *in* their teaching practice, not just knowledge that may be used *for* teaching practice. Though both are important, knowing what teachers know *for* teaching does not necessarily mean that knowledge is used *in* teaching practice.

The content knowledge for teaching framework has minimally been used in science education and the few studies that have used it only studied a few sub-domains of teachers’ knowledge. For example, Johnson and Cotterman (2015) discussed the relationship between two sub-domains of PCK with teachers’ knowledge of the science concepts. They found that discussing students’ science ideas in video club discussions became catalysts for the preservice teachers’ development of their knowledge of the science concepts. The content knowledge for

teaching framework has also been used to discuss how elementary and secondary teachers draw on their knowledge of the science concepts and their knowledge of students' ideas during their science instruction (Goodhew & Robertson, 2017; Robertson et al., 2017). Also, Nixon, Campbell, and Luft (2016) used the distinction of different sub-domains of SMK in the content knowledge for teaching framework to explain secondary preservice chemistry and biology teachers' strengths in explaining science concepts in their own disciplines compared with their challenges providing accurately sequenced chemistry knowledge (Nixon et al., 2016).

Even fewer studies have used the content knowledge for teaching framework with elementary science teachers and, thus far, this work has taken place only in the form of multiple choice assessments (Mikeska, Kurzum, Steinberg, & Xu, 2018; Mikeska, Phelps, & Croft, 2017). Specifically, Mikeska and colleagues (2017) developed an assessment of elementary teachers' content knowledge for teaching science and highlighted the connection between their knowledge and their teaching practice. While making an important contribution to how the content knowledge for teaching framework could be used in elementary education, this assessment has only been piloted with elementary teachers and it assessed elementary teachers' knowledge *for* teaching. Further work is needed to determine how the content knowledge for teaching framework could inform the study of elementary science teachers' knowledge in and for teaching practice (National Academies of Sciences Engineering and Medicine, 2015; Van Driel et al., 2014).

Summary: Literature on Science Teachers' Knowledge

Teachers' subject matter knowledge and pedagogical content knowledge of science concepts have been well studied over the years, but not often studied together or in relation to teaching practice. Also, little has been done to study teachers' subject matter knowledge and

pedagogical content knowledge of the science practices. Further work is needed to investigate teachers' knowledge in elementary science. Doing so would not only expand the field's understanding of elementary teachers' knowledge of science, but also provide insights into where teachers need further support for engaging in teaching that would support students in becoming scientifically literate citizens. My dissertation study begins to fill these gaps.

Opportunities to Learn that Support Teacher Knowledge Development

Teacher learning is situated and distributed within and across professional contexts (e.g., teacher education programs and school contexts). Opportunities to learn to teach within the contexts need to be distributed across different resources (Putnam & Borko, 2000). Examples of resources include coursework, classroom observations, and experiences teaching, among others. Within those resources, opportunities to learn can support novice teachers' development of their knowledge in and for teaching science.

Opportunities to learn have been defined in both narrow and broad ways. Building from Carroll's (1989) description of opportunities to learn, I include any activity that supports developing knowledge in and for teaching science. For example, an opportunity within a course in a teacher education program can include a discussion about students' alternative science ideas. As Carroll (1989) emphasized, time given to learn is a critical opportunity that is often overlooked. The opportunity in the teacher education course provides novice teachers time to develop their understanding of students' ideas and challenges with science concepts and practices. Characterizing the opportunities to learn that novice teachers have to develop their knowledge in and for teaching is critical if we are to identify ways to better support their knowledge development and therefore their teaching practice.

Rarely have studies investigated how opportunities to learn can support teachers' knowledge development over time (Van Driel & Berry, 2017). Most studies that investigate how to support teachers' knowledge development tend to be situated in a single course or a single teaching experience (Van Driel & Berry, 2017). The few that do look across programs tend to identify experiences preservice teachers have during their programs and not how the opportunities within those experiences support teachers' knowledge development (e.g., McDonald et al., 2011). Other studies have used course syllabi, program documents, and teacher surveys to evaluate teacher education programs for their effectiveness (Darling-Hammond, 2006a; Rickenbrode, Drake, Pomerance, & Walsh, 2018), but did not look at what particular opportunities in the programs supported the teachers' development. Similarly, few studies have considered how teacher education programs and school contexts can support (or not) teachers' knowledge in and for teaching (McDonald et al., 2011; Van Driel & Berry, 2017). Appleton and Kindt (2002), for example, is one of the few studies that investigated opportunities within school contexts that could support practicing elementary teachers' knowledge development. We know there are many resources that teachers can draw on to develop their knowledge in and for teaching science (Rivera Maulucci, 2013), yet we know very little about how those resources provide opportunities that support knowledge development. This dissertation begins to fill that gap by studying, in detail, how the opportunities to learn within a practice-based teacher education program and school contexts provided supports for novice elementary teachers' knowledge development in order to identify areas in need of further support.

Similar to other studies of novice teachers' knowledge development (D. Anderson & Clark, 2011; Appleton, 2003; Loughran et al., 2008; Van Driel et al., 2002; Van Driel et al., 1998; Zembal-Saul et al., 2000), the novice elementary teachers in this dissertation begin their

formal instruction during a teacher education program. During teacher education programs, opportunities to learn include classroom observations, disciplinary coursework, teacher education coursework, and experience teaching (Grossman, 1990; Shulman, 1987; Van Driel et al., 2002) that are designed to support their knowledge development. Often the experiences provide multiple iterations of planning, instruction, and reflection to help novice elementary teachers make sense of what it means to engage students in science learning (Windschitl et al., 2008; Zembal-Saul, 2009; Zembal-Saul et al., 2000).

The school environment is another context in which the novice elementary teachers in this dissertation continue their development as teachers. While in schools, teaching provides many opportunities for novice teachers to develop their knowledge in and for teaching (Mulholland & Wallace, 2005; Van Driel et al., 2002; Walberg, 1977; Zembal-Saul, 2009). Novice teachers may also have opportunities to learn when participating in professional development experiences, using curriculum materials, and interacting with their principals and/or colleagues, among other resources (Arzi & White, 2008; Davis et al., 2014; Rivera Maulucci, 2013). The following sections expand on the opportunities to learn within (a) teacher education, (b) experiences teaching, (c) school environments, and (d) curriculum materials.³

Practice-Based Teacher Education

Practice-based teacher education can support the development of knowledge and practices for elementary science teaching. Taking a learner-centered perspective, practice-based teacher education articulates teacher learning as situated, social, and distributed (Putnam &

³ In school contexts, other resources exist that may support novice teachers' knowledge development (e.g., professional development experiences) (Ball & Cohen, 1996; Grossman, 1990; Roth et al., 2011; Walberg, 1977), but those outlined in this study are resources for which I collected data.

Borko, 2000). The experiential learning opportunities provided for novice elementary teachers reflect teaching experiences in classroom settings (Dewey, 1916). They are developed from studying teaching practice and backwards mapping to what novice teachers need to know and be able to do in order to engage in the work of teaching (Ball & Forzani, 2009). The backwards mapping involves decomposing teaching practice into smaller parts that are more manageable for novices to learn (Grossman, Compton, et al., 2009). The decomposed parts become high-leverage teaching practices that guide the design of practice-based teacher education (Ball & Forzani, 2009; Grossman, Hammerness, et al., 2009).

A basic tenet of practice-based teacher education is that novice teachers study representations of teaching practice and rehearse how to engage in the high-leverage teaching practices demonstrated in those representations (Ball & Forzani, 2009; Grossman, Compton, et al., 2009; Lampert, 2010). The representations portray the decomposed aspects of teaching practice. For example, in learning how to teach elementary science, a representation of teaching practice could be a video clip of a teacher asking questions while moving from group to group during a science investigation. The learning focuses on the types of questions asked and how the teacher engaged students in sensemaking about the phenomena (the decomposition).

Practice-based teacher education also engages novice elementary teachers in continued, repeated opportunities to practice or rehearse the work of teaching referred to as approximations of practice (Ball & Forzani, 2009; Grossman, Compton, et al., 2009; Lampert, 2010). For example, novice teachers may rehearse with a small group of their peers and a teacher educator how to conduct a science sensemaking discussion focused on helping the “students” analyze data to inform the construction of a scientific explanation and argument. The teaching practices would

be leading a discussion, using representations to aide in data analysis, and supporting students' construction of an explanation and argument.

The decomposed aspects of teaching narrow the focus of the targeted learning in teacher education programs allowing for more reachable goals for novice elementary science teachers (Roth, 2014). So far, only hypotheses have been made as to *what* opportunities practice-based teacher education provides for supporting novice elementary teachers' knowledge development (Lampert et al., 2013; Steele, 2006; Windschitl, Thompson, Braaten, & Stroupe, 2012). Further work is needed that investigates *how* these learning opportunities can support novice elementary teachers' knowledge development.

Experiences Teaching Elementary Science

Novice teachers develop an understanding of science teaching and learning through their own experiences as students and initial teaching experiences. Lortie's (1975) *apprenticeship of observation* emphasized how learning about teaching has its roots in teachers' experiences as students observe teachers. Learning from observing teachers and engaging in teaching can support novices' learning about teaching (Appleton & Kindt, 2002; Cochran-Smith & Lytle, 1999; Loughran, 2014; Van Driel et al., 2002; Van Driel et al., 1998). For example, the activities in-service elementary teachers use when teaching science can support or hinder their knowledge development (Appleton, 2003). Also, the interactions with students during science lessons can help teachers develop their knowledge of students' challenges with science concepts (Van Driel et al., 2002). Overall, we know teaching experience helps teachers develop their knowledge for teaching (Mulholland & Wallace, 2005), but there is limited research investigating how teaching experiences support teachers' knowledge development.

School Context

There are many resources in a school context (Rivera Maulucci, 2013), but few studies have investigated how those resources support teachers' knowledge in and for teaching (Loughran, 2014). (Curriculum materials are an exception and I discuss these in the following section.) The studies that have investigated the influence of school resources on teaching tend to focus on how the resources influence teaching practice and not on teacher knowledge. For example, support from colleagues, adequate resources, staff stability, instructional coherence, distribution of responsibilities, and how a school emphasizes science learning can influence how teachers engage their students in science (Appleton & Kindt, 2002; Larkin, Seyforth, & Lasky, 2009). In some cases, if a teacher feels the school does not encourage science instruction, they are less likely to teach science at all (Ramey-Gassert, Shroyer, & Staver, 1996). When they do, they rely on instructional moves that do not typically support students' scientific sensemaking (e.g., students read textbooks and give presentations, students do not interact with phenomena). In comparison, communities of practice and curriculum materials have the potential to support teachers' knowledge development and teaching practice (e.g., Akerson, Cullen, & Hanson, 2009; Davis et al., 2014).

Curriculum Materials. Curriculum materials are tools that can support elementary teachers' knowledge and practices related to science teaching (e.g., Arias, Bismack, et al., 2016; Arzi & White, 2008; Beyer & Davis, 2009a, 2012; Davis & Krajcik, 2005; Davis, Palincsar, Smith, Arias, & Kademian, 2017; Remillard, 2005; Schneider, 2013). For example, Arzi and White (2008) found that, over time, the most influential resource supporting secondary teachers' knowledge development were the curriculum materials. Educative curriculum materials – aspects of curriculum materials designed to educate the teacher – have also been found to support

elementary teachers' knowledge development (Arias, Bismack, et al., 2016; Beyer & Davis, 2009b, 2012; Bismack et al., 2015; Davis & Krajcik, 2005; Davis et al., 2017; Lin, Lieu, Chen, Huang, & Chang, 2012; Schneider, 2013; Schneider & Krajcik, 2002). Curriculum materials provide potential for supporting teachers' knowledge development.

Summary: Opportunities to Learn

The research is narrow in scope when studying how opportunities to learn in teacher education programs and school contexts can support teachers' knowledge development. Except for studies of curriculum materials, communities of practice, and professional development there is limited research on what learning opportunities exist in elementary school contexts (e.g., principals, other colleagues). The studies that do exist typically focus on supporting teaching practice and not knowledge development – with some exceptions of studies of curriculum materials and professional development (e.g., Arias, Bismack, et al., 2016; Davis et al., 2017; Roth et al., 2011; Schneider, 2013; Schneider & Krajcik, 2002). My dissertation begins to fill this gap by investigating how the opportunities to learn in a practice-based teacher education program and school contexts support novice elementary teachers' development of their knowledge in and for teaching science.

Theoretical Framework for Content Knowledge for Teaching Science

Content knowledge for teaching science is knowledge in and for teaching practice, which means it is important to consider the role of teaching practice and contexts on influencing teacher knowledge development. Figure 2-2 represents the relationships among teacher knowledge, teaching practice, and contexts that provide unique opportunities to learn. The dashed boundaries between each circle represent the fluidity of knowledge in relation to the other dimensions. Studying knowledge in teaching practice can provide insights into how teachers use their

knowledge to inform their teaching, which is currently lacking in the literature on teacher knowledge.

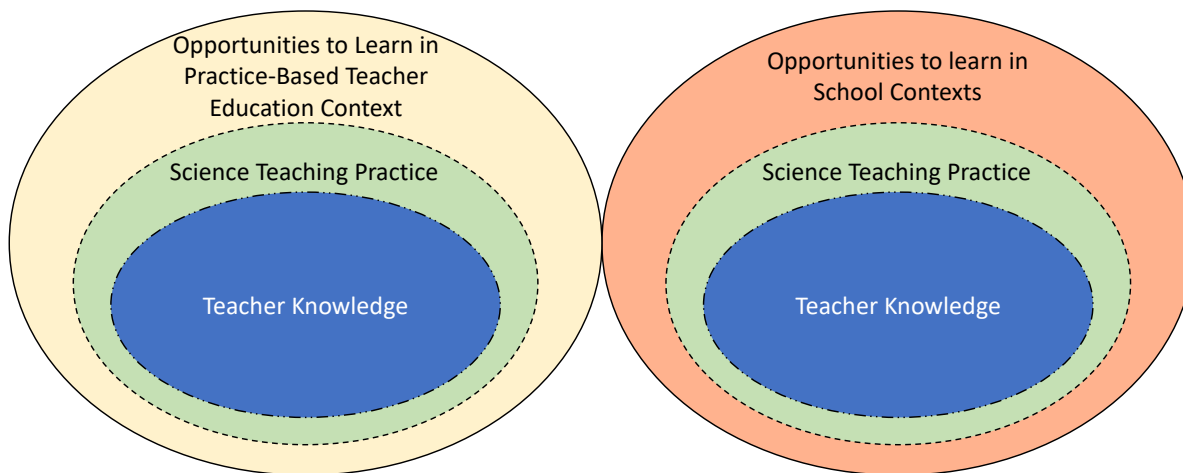


Figure 2-2. Studying the Content Knowledge for Teaching Science framework

The content knowledge for teaching framework (see Figure 2-3) is deeply integrated with what knowledge teachers draw on in their practice and articulates sub-domains of SMK that had not previously been investigated (Ball & Bass, 2000, 2003; Ball et al., 2008). Because it was developed in mathematics education (Ball et al., 2008) there are aspects important for science teaching that are missing in the framework. For this reason, I expand the content knowledge for teaching framework to be specific for science teaching (see Figure 2-4). Figure 2-4 explicates what I consider to be teacher knowledge noted in the innermost circles of Figure 2-2.

Importantly, teachers need specific SMK and PCK for each disciplinary core idea, crosscutting concept, and science practice as outlined in the NGSS. This is demonstrated by the triangular images in Figure 2-4, which refer to disciplinary core ideas (DCI), crosscutting concepts (CCC),

and science and engineering practices (SEP).⁴ I also included two new sub-domains and modified the language of a third sub-domain. I discuss these in the following sections.

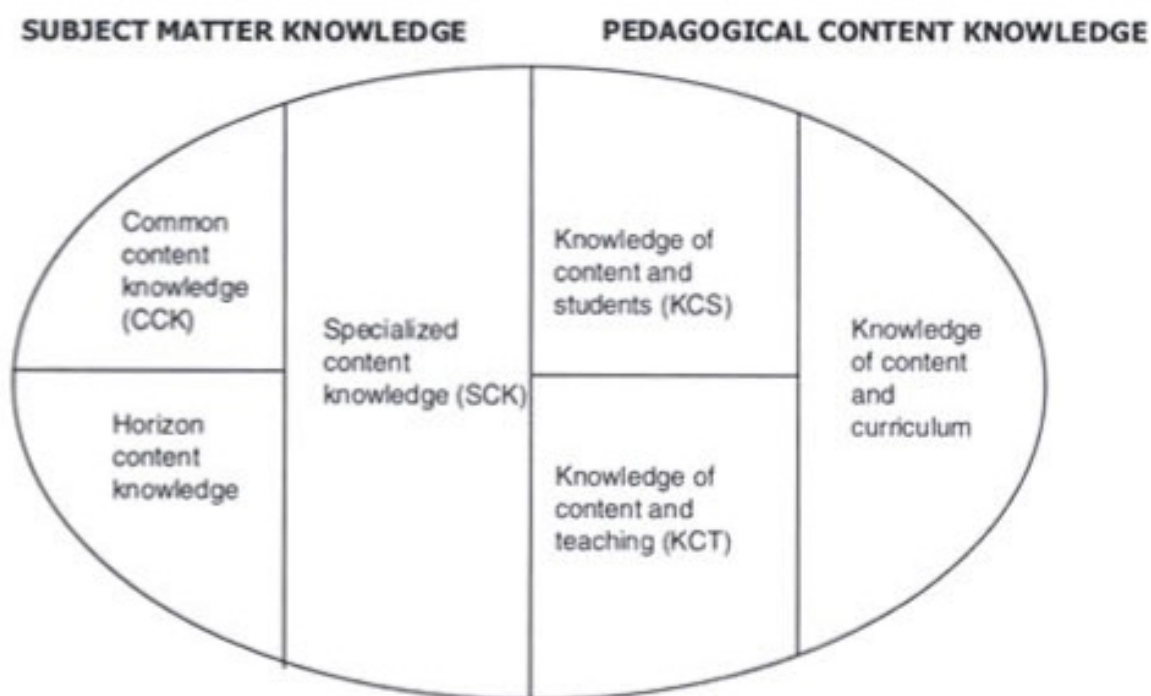


Figure 2-3. Content Knowledge for Teaching framework (Ball et al., 2008)

⁴ Distinguishing between the disciplinary core ideas and crosscutting concepts is important yet I do not do so in this dissertation because I do not have data that clearly delineates the two dimensions.

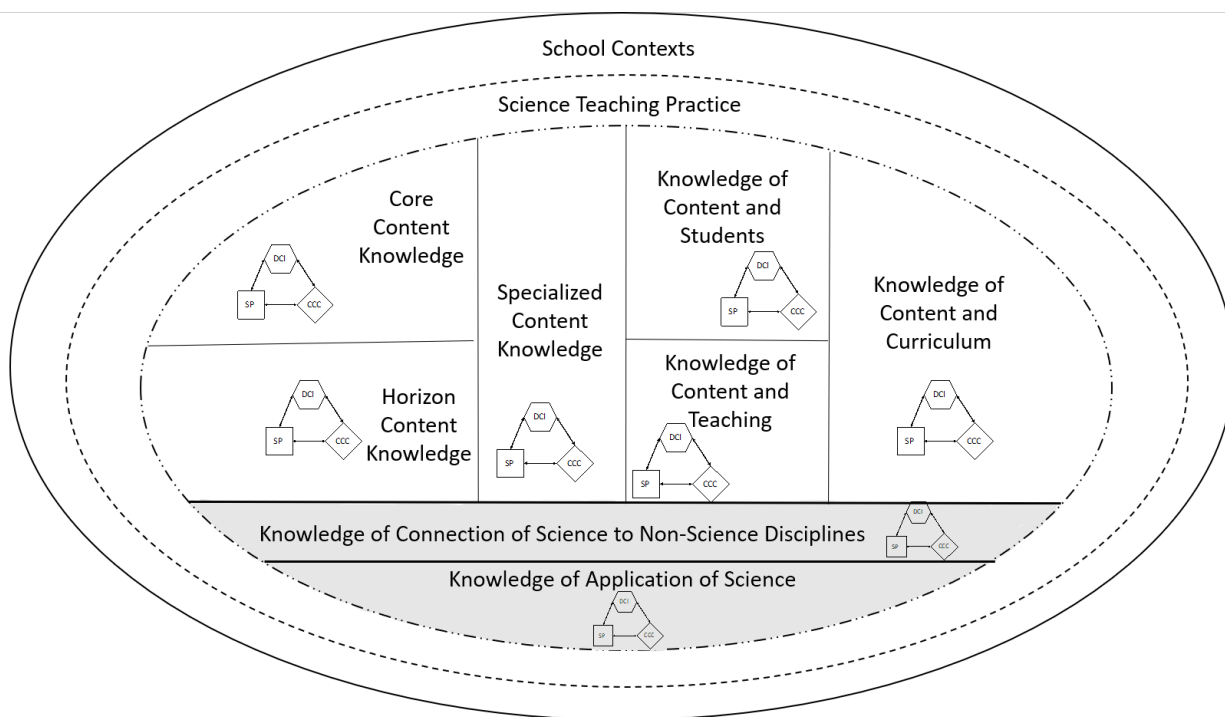


Figure 2-4. Content Knowledge for Teaching Science (CKT-S) (Adapted from Ball et al., 2008; and drawing also on Davis & Petish, 2005; Kloser, 2014; Magnusson et al., 1999; Nixon, Toerien, & Luft, 2019; Shulman, 1986, 1987)

Content Knowledge for Teaching Science Framework: Subject Matter Knowledge

Teachers' subject matter knowledge, located on the left side of Figure 2-4, refers to teachers' knowledge of the science concepts and practices, as well as their flexibility in understanding the concepts and practices for the purposes of teaching (Ball et al., 2008; Ma, 1999). Ball and colleagues (2008) refer to this as "knowledge and skill important for teaching yet not entailing knowledge of students or teaching" (p. 398). In the content knowledge for teaching science framework, the sub-domains of subject matter knowledge include core content knowledge, horizon content knowledge, and specialized content knowledge. As explicated by Nixon, Toerien, and Luft (2019) core content knowledge (CCK; similar to common content knowledge in the Ball et al., 2008 framework) is an understanding of science concepts, practices,

and mechanisms that a person is assumed to have once they graduate from high school. An example is a molecular understanding of how condensation forms.

Horizon content knowledge is “an awareness of how...topics are related over the span of...the curriculum” (Ball et al., 2008, p. 403). This is similar to Shulman’s (1986) notion of vertical curriculum knowledge which is the understanding of the concepts and practices previously taught in school and those that build on current classroom learning. For example, a teacher must know that students need to understand that there are particles smaller than what we can see before they can begin to understand the atomic molecular theory.

Lastly, specialized content knowledge is “knowledge and skill unique to teaching... [and is] not typically needed for purposes other than teaching” (Ball et al., 2008, p. 400). For example, this includes an understanding of the affordances and constraints of different representations of condensation and the ability to interpret the science of students’ ideas in-the-moment relating to condensation (Kademian, 2017; McDiarmid, Ball, & Anderson, 1989).

Content Knowledge for Teaching Science Framework: Pedagogical Content Knowledge

Teachers’ pedagogical content knowledge refers to the knowledge teachers draw on when constructing science learning environments that support students’ scientific sensemaking. In particular, this involves knowing how to engage students in the science concepts and practices in ways that are productive and uphold the integrity of the sciences. This includes knowing instructional strategies related to the concepts and practices, as well as students’ related ideas and relevant curricular resources, among others (Grossman, 1990; Van Driel et al., 1998). For example, a teacher’s pedagogical content knowledge related to condensation involves knowing when to introduce one or more representations based on an understanding of students’ challenges and alternative ideas related to condensation. It also involves knowing how to use careful

language to discuss condensation accurately while not leading to misconceptions. In this example, the teacher's pedagogical content knowledge includes their knowledge of students' alternative ideas about condensation and knowing how to put that into practice to use different representations of condensation in productive (e.g., introduced incrementally) ways that uphold the integrity of the discipline (e.g., not using language that can lead to misconceptions). Therefore, teachers' pedagogical content knowledge becomes "the knowledge that a teacher uses to provide teaching situations that help learners make sense of particular science content" (Loughran et al., 2001, p. 289), as well as making sense of the science practices.

In the content knowledge for teaching science framework, the sub-domains of pedagogical content knowledge include knowledge of content and students, knowledge of content and teaching, and knowledge of content and curriculum. Knowledge of content and students is an understanding of how students' ideas, experiences, and backgrounds relate to science concepts and practices (e.g., alternative ideas students have regarding condensation) (Ball et al., 2008; Bang & Medin, 2010; Shulman, 1986). Knowledge of content and teaching is an understanding of ways to engage students in science (e.g., knowing how to circulate and ask sensemaking questions during a scientific investigation) (Ball et al., 2008; Shulman, 1986, 1987; Wilson et al., 1987). Knowledge of content and curriculum is an understanding of how to read, interpret, and modify curriculum to inform teaching practice (Ball et al., 2008; Beyer & Davis, 2009a; M. W. Brown, 2009; Grossman, 1990; Wilson et al., 1987). Curriculum materials typically include assessments for students, which means knowledge of content and curriculum should also include a teachers' understandings of affordances and constraints of assessments.

Content Knowledge for Teaching Science Framework: Additional Sub-Domains

The CKT-S framework, as I have developed it here, includes two additional sub-domains that I hypothesize span subject matter knowledge and pedagogical content knowledge: (a) Knowledge of the connection of science concepts and practices to non-science disciplines and (b) Knowledge of the application of science. These sub-domains are shaded in Figure 2-4 to indicate that they are additional, newly developed sub-domains. Building from Shulman's (1986) lateral curricular knowledge, the knowledge of the connection of science to non-science disciplines is an understanding of how a science concept or practice relates to concept(s) or practice(s) in non-science disciplines (e.g., mathematics). For example, a teacher may connect their understanding of scientific predictions to predictions made in English language arts (Casteel & Isom, 1994). Elementary teachers, in particular, teach many subjects so understanding how concepts and practices within a single discipline or subject relate to those in other disciplines and subjects is important for supporting student learning.

The knowledge of the applications of science draws on the knowledge needed to engage in the teaching practice *Connecting Science to its Applications* (see Kloser (2014)). This requires teachers to know how science concepts or practices may appear in phenomena outside the lesson, as well as in social contexts. For example, a lesson about the structure and function of plant stems may involve studying how water moves up the xylem of a plant stem, but the teacher should also understand how this applies to other situations external to the lesson (i.e., when watering plants, we pour water on the soil not the leaves, because the water is absorbed through the roots and carried up the xylem in the stem). In this example, the teacher knows to connect their understanding of the structure and function of plant anatomy (drawing on core content knowledge) to phenomena that may be related to students' experiences (drawing on knowledge

of content and students). In this way, the knowledge of the applications of science spans SMK and PCK and can support students' understanding of science concepts and practices (Davis & Petish, 2005).

The next chapter outlines the methods, data sources, coding, and analyses for this dissertation study, as well as a description of each novice elementary teacher and their resources for teaching elementary science across the four years.

Chapter 3 Methods

I conducted a longitudinal case study (Merriam, 2009; Stake, 2000) using records of practice and program documents to investigate novice elementary teachers' development of their CKT-S over time, how it may influence their teaching practice, and how it relates to opportunities to learn CKT-S. The study spanned two years in a practice-based teacher education program and two years of teaching – four total years (2014-2018). The longitudinal nature of this dissertation allowed for rarely identified findings, because few studies investigate teachers' knowledge over time (Schneider & Plasman, 2011) or closely analyze opportunities to learn (e.g., Rickenbrode et al., 2018).

Role of the Researcher

I have worked in the practice-based teacher education program for four years. During the first year, I apprenticed in the elementary science methods course in the section in which the participants were students (referred to as interns), which included attending classes and participating in course planning. I worked with interns during group work and as a teacher educator during the peer teaching sessions where I gave guidance on their science teaching. I was, therefore, positioned as having elementary science teaching experience and was likely viewed as an authority figure due to my role as a science teacher educator and apprentice in the course.

After those experiences with the interns participating in this study, during the second year of my experience with the program, I co-taught the elementary science methods course with

Elizabeth Davis. I was an apprentice in the Teaching with Curriculum Materials course. The participants for this dissertation study were not interns at that time. During the third and fourth years, I taught the Workshop for Teaching Elementary Science in the Elementary Master's with Certification program. I also often participated as a teacher educator during peer teaching in the undergraduate elementary science methods course.

I also worked as a graduate student research assistant on the Ambitious Teaching: Trajectories of Elementary Science Teachers (ATTEST) research project. In this role, I conducted observations of and interviews with the participants during their student teaching experience in the teacher education program and their first-year teaching. Participants typically introduced me to the children in their classrooms as a "former teacher of how to teach science." I also coded and analyzed data from their science teaching experiences in the elementary science methods course and their student teaching experiences (Bismack, Davis, & Palincsar, 2017a). In this role I was positioned as a researcher and possible authority figure for elementary science teaching when interacting with the participants.

During this dissertation study, I positioned myself as an observer-participant (Hesse-Biber & Leavy, 2011), by foregrounding my role as an observer of the participants' teaching. Recognizing that the novice elementary teachers are continually developing their science teaching knowledge and practices, I supported them as opportunities arose. For example, I shared an article (Kur & Heitzmann, 2008) with Claudia about using students' ideas to guide instruction and I shared open-access curriculum materials (Michigan Virtual University & Science Mathematics Technology Center, 2017) with Diana who did not have any curriculum materials and was struggling to find resources. All support I provided was documented and considered when constructing case studies of the teachers.

Study Settings and Participants

Study Contexts for Years 1 and 2: The Teacher Education Program

The participants attended a practice-based, undergraduate teacher education program during their third (junior) and fourth (senior) years at a four-year institution. They took courses during their first year and a half in the program and participated in a student teaching experience during the final semester.

The practice-based teacher education program is guided by three pillars: high-leverage teaching practices, content knowledge for teaching, and ethical obligations (Davis & Boerst, 2014). The discipline-neutral high-leverage teaching practices are accessible and critical for novice elementary teachers to learn (Ball & Forzani, 2009; Ball, Sleep, Boerst, & Bass, 2009; Grossman, Hammerness, et al., 2009) and are designed to be re-worked by instructors to fit each discipline. The content knowledge for teaching pillar emphasizes the importance of elementary teaching being grounded in content that upholds the integrity of each discipline. Lastly, the ethical obligations guide the interns in facilitating ethically-grounded professional interactions with others. Within this program, interns engage in representations, decompositions, and approximations of teaching practice emphasizing the high-leverage practices, content knowledge, and ethical obligations (Grossman, Compton, et al., 2009). The teacher education program also assesses interns at different points in the program.

Study Year 1: Children as Sensemakers Course. The Children as Sensemakers course occurred during the interns' first year in the program. This one-credit, four-week course supported interns in learning how to provide students with opportunities to share their ideas and make sense of science concepts. The course focused on eliciting students' ideas and interpreting, facilitating, and assessing students' sensemaking about two everyday natural phenomena (day

and night cycle; what makes sound and how sound changes). The assignments for the course included a description of the student's science ideas, an analysis of an interactive reading, and an analysis of an interview with the student.

Study Year 1: Teaching with Curriculum Materials Course. The Teaching with Curriculum Materials course also occurred during the interns' first year in the program. The one-credit course supported interns in learning how to evaluate and modify curriculum materials based on the lesson goals and assessments. The interns completed a final assessment where they evaluated and modified a second-grade science lesson on buoyancy.

Study Year 2: Elementary Science Methods Course. The elementary science methods course was a two-credit, nine-week course taken during the second year in the program. This course was paired with a classroom field experience in kindergarten through the eighth grade, where the interns taught and interacted with elementary students. The intent of the course was to help interns learn how to teach investigation-based science lessons which were divided into three segments: *engage* (introduce the science topic and investigation question), *experience* (students conduct an investigation to collect data), and *explain with evidence* (students analyze their data to use as evidence to support scientific explanations) (Benedict-Chambers, 2014; Kademian & Davis, in press) similar to and based loosely on the 5E Model (Bybee et al., 2006). During the course, the interns participated in approximations of practice where they taught each of these segments to a small group of peers and a single teacher educator (referred to as peer teaching). The interns also watched videos and analyzed student work (as representations of practice) to reflect on ways teachers engage in aspects of science teaching.

The two main assignments for this course were the Small Scale Science Teaching (SSST) lesson and the Full Scale Science Teaching (FSST) lesson. For the SSST assignment, the interns

taught the *experience* portion of a science lesson to elementary students in the field and reflected on their teaching. For the FSST assignment, the interns planned, taught, and reflected on an entire science lesson in the field.

Study Year 2: Student Teaching. Continuing in the same elementary classroom, the interns engaged in a full-time student teaching experience during the second semester of the second year in the program. The participants in this study were either in the Arlington School District or the Wagner School.⁵ The Arlington School District is a highly-resourced, large public school district with science curriculum materials. The Wagner School is a county-wide, International Baccalaureate middle school with no science curriculum materials. The main assignment during student teaching was the design and teaching of a unit plan in a discipline of the interns' choice (potentially science). The unit length varied.

Study Contexts for Years 3 and 4: First and Second Years of Teaching

During years three and four of the dissertation study, the novice elementary teachers (previously interns in the practice-based teacher education program) taught in elementary schools across the United States. The data collected from the novice teachers' classrooms included lesson plans, videorecords of science instruction, and interviews with the novice teachers. The data collected about the schools and districts include interviews with principals, teacher surveys about the resources within the schools (e.g., sinks, science room), and any other documents (e.g., school improvement documents) that included information about science teaching and learning. I used these resources to characterize the learning opportunities supporting the development of the novice teachers' CKT-S in the schools. I discuss these data sources in more detail in the sections below.

⁵ Pseudonyms are used for all schools, districts, and participants.

Participants and Selection of Participants

The novice elementary teachers invited to participate in this dissertation study were former interns in the practice-based teacher education program. During the practice-based teacher education program, the three novice teachers were part of a cohort of 46 undergraduate elementary teaching interns. The cohort was representative of U.S. elementary teachers (e.g., mostly female, white, middle-class). The three novice teachers were invited to participate in the ATTEST project as part of a focal group of eleven novice elementary teachers. The teachers within the focal group were invited to participate due to representing some diversity among the undergraduate elementary teaching cohort, which included being science majors, novice teachers of color, male novice teachers, achieving high science scores on state and national assessments, and/or as strong participants during the Elementary Science Methods course. In other words, they were previously chosen as focal novice teachers in the ATTEST research project due to their atypicality (Stake, 2000).⁶ Of the novice teachers in the focal group, six novice teachers participated during their first year of teaching (study year 3) and three teachers participated during their second year of teaching (study year 4). In this dissertation, I focus only on the three participants who participated throughout all four years of the study: Claudia, Harry, and Diana. Participation was voluntary, and their confidentiality and anonymity were kept secure. See Table 3-1.

⁶ See Davis and Palincsar (under revision) for further details about the selection of these participants.

Table 3-1. Information about Participants in Dissertation Study during Study Years 2, 3, & 4

Participants	Year 2		Year 3		Year 4	
	District	Grade	District	Grade	District	Grade
Claudia	Wagner School	6	Ruby Orchid School District	5	Ruby Orchid School District	5
Harry	Wagner School	6	Oxbow School District	4	Oxbow School District	4
Diana	Arlington School District	K	Arlington School District	5 & 2 (long-term sub)	Hannah School	5

In the following sections I draw on the Rivera Maulucci (2013) framework outlining resources for supporting science teaching to describe the school contexts in which each novice teacher worked. The resources discussed in the descriptions are based on what the novice elementary teachers (interviews and surveys), mentor teachers (interviews), and principals (interviews) viewed as resources for science teaching. I identified the resources (e.g., curriculum materials, professional development opportunities, time for science, parental involvement) using emergent coding (Charmaz, 2004). In the descriptions below, I discuss the levels in which the resources were situated, which were the classroom-, school/district-, or community-levels. The stated resources spanned all five types of resources noted in the Rivera Maulucci (2013) framework (material, social, symbolic, cultural, and strategic), but the inconsistency and difficulty in determining the exact type of resource led to the decision to not discuss the types in the descriptions below.

Claudia. Claudia is a white, female teacher in her early twenties. She grew up in a suburban, middle class neighborhood. Her degree is in elementary education with a focus on

English language arts, though she also had high science scores on incoming standardized assessments. Claudia was also a strong student in the Elementary Science Methods course.

Claudia student taught in a diverse, International Baccalaureate (IB) middle school (greatschools.org, 2018) where students had different teachers for different subjects. The sixth-grade science teacher was not one of Claudia's main mentor teachers, but Claudia did observe the science teacher when her group of sixth-grade students were in science class. For this reason, she had few opportunities to engage in science teaching during her student teaching experience. Even with few opportunities, Claudia mentioned classroom- and school-level resources that informed her few science teaching experiences. She mentioned using online resources due to a lack of curriculum materials (and the classroom's focus on technology), not having physical materials for science, and the science mentor teacher's didactic teaching methods that mainly focused on vocabulary and language-development. Claudia commented that the science teacher "buys everything herself," which is why she does not engage her students in "a lot of investigation or experience-based teaching" (Y2 Claudia Interview 1).⁷ This way of teaching differed from how the novice teachers were taught how to teach science in the Elementary Science Methods course. For this reason, Claudia discussed using her student teaching experience to consider ways of teaching science that differed from the science teacher's didactic teaching methods (Y2 Claudia Interview 1).

In contrast to her student teaching experience, during her first two years of teaching Claudia taught fifth grade in a suburban elementary school in the Midwest. Approximately 83%

⁷ Data source abbreviations refer to the year in the study (e.g., Y2), teacher or course, and type of source (e.g., video, interview, lesson plan). The course abbreviations are ESM (Elementary Science Methods), CaSM (Children as Sensemakers), and TwCM (Teaching with Curriculum Materials).

of the students at the school are white, 8% are two or more races, 5% are African American, 3% are Hispanic, and about 1% are Asian. Also, about 22% of the students receive free or reduced lunches (greatschools.org, 2018). The school is an International Baccalaureate (IB) school, which means they use an IB curriculum that aims to integrate content areas around related themes (e.g., systems) (Y2 Claudia Principal Interview).

Claudia discussed resources at the classroom and school/district levels during her first two years of teaching (Rivera Maulucci, 2013). At the classroom level, the resources were about the usefulness of the curriculum materials with some modification to meet the needs of her students, as well as about time management and not having enough time for teaching science (Y3 Claudia Interviews 1, 2, 3; Y4 Claudia Interviews 1, 2, 3; Y3 Claudia Surveys; Y4 Claudia Surveys). For example, when discussing the usefulness of the curriculum materials with modifications Claudia mentioned changing the

Butterflies and the compost system into a more intentional investigation... I created the investigation sheet for the compost system where I really forced [the students] to write out their hypothesis, intentional observations. We wrote conclusions. There was a procedure, and then as well for the butterflies, just making this little booklet of observing-drawing observations, recording, noting their nutrients, and then using that learning to guide their final assessment...But obviously, if you looked at the curriculum, there's so much in this unit (Y4 Claudia Interview 2).

Claudia frequently discussed the usefulness of the curriculum materials for knowing what to teach and also for developing her own core content knowledge of the science concepts (Y3 Claudia Interviews 2, 3; Y4 Claudia Interviews 1, 2, 3).

At the school/district level, Claudia discussed her grade-level colleagues, the IB curriculum, and the limited professional development opportunities for supporting her science teaching. Claudia is someone who appreciated thoroughly planning with colleagues, which she did during student teaching with Harry, the other intern at her school. In comparison, during her first two years of teaching Claudia's colleagues were less focused on thorough science planning (Y3 Claudia Interview 3) and less likely to teach science (Y4 Claudia Interview 1) than was Claudia. This challenge was apparent for Claudia when she mentioned,

I'm on a team of three. And I have taught more science individually than them combined. And so, it just is so quickly the thing that is pushed aside... So, I think that's been hard because I do feel like I'm doing a lot of this on my own and trying to make it work and do it well and not rob my students of a science education (Y4 Claudia Interview 1).

Claudia also mentioned the IB focus of the school being both supportive and challenging for her science teaching. With the focus on students "being thinkers and independent learners and also inquirers" (Y4 Claudia Interview 3), the IB orientation of the school aligned with her views of science as investigation-based. However, it did constrain her science teaching due to time taken away from science for students to work on summative, IB, capstone projects (Y3 Claudia February, June Surveys; Y4 Claudia Interview 2; Y4 Claudia May, June Surveys).

Lastly, Claudia had some opportunities for science-related professional development that focused on using a KLEWS chart (Hershberger & Zembal-Saul, 2015) and incorporating science practices in science instruction (Y3 Claudia Interview 3; Y3 Claudia May Survey; Y4 Claudia Interviews 2, 3). After that opportunity, she incorporated a KLEWS chart in her science teaching during her second year of teaching. Overall, the resources supporting Claudia's science teaching were mainly situated at the classroom and school/district levels.

Harry. Harry is a white, male novice elementary teacher in his early twenties. He is from an English-speaking country outside the United States. Similar to Claudia, Harry's degree is also in elementary education and he was a strong student in the Elementary Science Methods course. Harry's student teaching experience was similar to Claudia's in that he also worked with a sixth-grade class in the Wagner School. He worked with the same science teacher and also commented on the constraints of not having curriculum materials or physical materials for science (classroom-level resources) (Y2 Harry Interviews 1, 2).

During his first- and second-years teaching, Harry was a fourth-grade elementary teacher in a diverse public school on the west coast. Approximately 83% of the students in the school are Hispanic, 11% are African American, 2% Asian, 2% Bi-Racial, 1% White, and 1% Hawaiian Native/Pacific Islander. Also, about 57% are English Language Learners (ELL) and 85% of students receive free or reduced lunch (greatschools.org, 2018). According to the principal, this school was re-organized and re-named about 10 years ago with the focus of the new school on increasing test scores (by focusing on language development due to the high number of ELL students) and retaining teachers (the district has a high teacher turnover rate) (Y4 Harry Principal Interview).

During his first two years teaching in the Oxbow School District, Harry discussed different resources at the classroom-, school/district- and community-levels (Rivera Maulucci, 2013) that supported his science teaching in different ways. At the classroom level, Harry mentioned that the district-modified FOSS science kits were the most useful resource in supporting his science teaching, which he regularly mentioned during interviews (Y3 Harry Interviews 1, 2, 3, 4; Y4 Harry Interviews 1, 3). Though they supported Harry's science

instruction, he did mention needing to modify the materials to be more student-centered and investigation-based. For example, he said,

In the unit materials that I'm using I was told to just go through the steps and we all together go through and create the circuit and light the bulb together... that's definitely been one of the ways that I've adapted science unit materials a lot this year is being able to allow for some more freedom and some more exploration (Y3 Harry Interview 4).

Even though Harry had useful curriculum materials, he still struggled with not having enough time to teach science (Y3 Harry Interview 1; Y4 Harry Interviews 2, 3; Y3 Harry December, February Surveys). This was due to the district's focus on increasing mathematics and English language arts assessment scores, thereby limiting time for science or social studies (Y3 Harry Principal Interview).

At the school level, grade-level teachers and parents were resources for Harry's science teaching, while district policies and professional development varied in how they influenced his science teaching. Harry mentioned planning science with the other grade-level teachers and sharing resources, though he was not sure the extent to which they were teaching science (Y3 Harry Interviews 1, 4; Y4 Harry Interviews 1, 3). That could be due to the district's limited attention placed on science teaching compared with mathematics and English language arts. Harry and his principal commented that science is not given extensive time in schools compared to mathematics and English language arts in part because the report cards do not extensively attend to science and science is not part of the school's inquiry cycles. Also, the teachers were not given time for science professional development (Y3 Harry Interview 1; Y4 Harry Interview 3; Y3 Harry Principal Interview). Even with those constraints, Harry did find ways to draw on

his students' families' science-related careers (e.g., construction workers) and native language to support his science teaching (Y3 Harry Interview 1; Y3 Harry Principal Interview).

Lastly, at the community level, Harry discussed working with an environmental organization who came into his classroom during his first-year teaching and taught a science unit on watersheds and ecosystems while he observed the instruction. He then taught the same unit during his second-year teaching. He discussed this as a resource saying,

I feel really confident because I really have appreciated the model of them... teaching for us and us observing them teach and then teaching ourselves... Even though it was a whole year ago, I'm still drawing on a lot of the little nuances that I observed. And then, I can still adapt it in the way that I see fit, which is nice as well (Y4 Harry Interview 1).

The environmental organization provided an external, community-based resource for supporting Harry in connecting his science teaching to the surrounding natural environment where the school and district are located.

Overall, Harry mentioned the classroom-level resources being the most influential resources for his science teaching, particularly the curriculum materials. Even with his focus on the classroom-level resources, the district's policies and decisions (including decisions about the curriculum materials) influenced how he taught science and the frequency of his science teaching.

Diana. Diana is a white, female novice elementary teacher in her early twenties. She grew up in a suburban, upper middle class neighborhood in the Midwest. Her degree is in elementary education and she was a strong student in the Elementary Science Methods course. Diana student taught in Kindergarten in the Arlington School District where she discussed using classroom- and school/district-level resources. She mentioned that the kindergarten curriculum

materials were “awful” because the information for each lesson was short and did not encourage teachers to have students make sense of science concepts (Y2 Diana Interview 2). When discussing school/district resources, Diana commented that “there were no outcomes for the district [for science in kindergarten] other than [students] participated” (Y2 Diana Interview 2). She also invited parents and school personnel in the classroom to discuss how they used body parts for their hobbies and careers. For example, Diana mentioned that she invited a bird watcher in to talk about how “she used her five senses when observing and studying birds. And we had a dancer and a personal trainer [discuss how they used their] muscles” (Y2 Diana Interview 2). Overall, Diana was able to draw on classroom- and school/district-level resources during her student teaching experience, even with the constraints of the curriculum materials.

During her first-year teaching, Diana was a long-term substitute teacher in a fifth-grade and a second-grade classroom in the Arlington School District. She had the same curriculum program as in student teaching but above the kindergarten level, the materials provided more information for each lesson. Even with more in the curriculum materials, she still talked about using other resources to find handouts, student-friendly materials, and to expand her own core content knowledge of the science concepts. For example, she mentioned

I’ve had to look outside the curriculum to answer questions that I had myself to make sure that I had enough background knowledge, like with the caterpillars’ poop part of it (Y3 Diana Interview 2).

In this example and others, Diana commented on going beyond the curriculum materials to expand her own science knowledge. At the classroom-level, she also discussed challenges in finding time for science. At the school/district-level, Diana mentioned participating in a professional development opportunity focused on using read-alouds to support science

instruction (Y3 Diana May Survey). During Diana's first-year teaching, she discussed classroom- and school/district-level resources as influencing her science teaching in varied ways.

During Diana's second-year teaching, she was a fifth-grade teacher in a K-8 independent, religious-based school in the Midwest, teaching science to two fifth-grade classes.

Approximately 97% of the students are white and 3% are African American (greatschools.org, 2018). In Diana's classroom, over 64% of her students are English Language Learners with Arabic as the native language. Though not racially diverse, the students' culture and religion differed from Diana, which influenced all aspects of Diana's teaching. For example, Diana mentioned that

I have so many kids from Syria. I didn't know that like 80% of my class is Syrian... one day, someone started chanting something. And I was like, "What does that mean, S.?"

And it was something like, "Freedom to the people. Overthrow the government." And I was like, whoa... [Also], I just recently moved... And so, I was able to give some of my stuff to [a new student from Syria] (Y4 Diana Interview 2).

As this example demonstrates, students' community-based experiences that were not necessarily science-related played a role in how Diana engaged in her teaching, not just science teaching. She even went to religious events with her students' families outside of school as ways to connect with students (Y4 Diana Interview 3). The students' cultural and religious influences were apparent throughout Diana's teaching experience, though science-related resources were less prevalent.

Diana struggled with lacking resources at the classroom- and school/district-levels. At the classroom-level, there were no science curriculum materials which was challenging for Diana. For this reason, I shared the open-access Phenomenal Science curriculum materials (Michigan

Virtual University & Science Mathematics Technology Center, 2017) with Diana, which became the unit she taught for this dissertation. When using those curriculum materials, she commented on the usefulness of having a driving question for the unit already created stating,

I think the hardest thing for the curriculum was finding those driving questions, like, how is everything tying in together?... That's really hard to come up with... so that was really, really useful to use [in the Phenomenal Science curriculum] (Y4 Diana Interview 3).

Though, she did struggle with some aspects of the curriculum materials mentioning that particular lessons were difficult to make sense of and that some readings were not student-friendly, particularly for her ELL students, referring to one as a “college-level research paper” (Y4 Diana Interview 2).

The school/district-level resources were also lacking in that she did not have any science-related professional development opportunities and did not have other colleagues to collaborate with. She was part of a third-fifth grade Professional Learning Community (PLC), but commented that “there was never really a focus” to the PLC meetings (Y4 Diana Interview 3). Diana also mentioned wanting to utilize parents’ science-related careers, as she did during student teaching, but that school policies prevented this. For example, she commented that

I think the school also kind of does not encourage families to come in because they don't let siblings come... And a lot of the mothers who can come in because they're stay-at-home moms... need to bring their siblings... Like Z's mom, was a pharmacist before she became stay-at-home. A lot of them had a lot of work experience, but they can't bring their younger siblings in (Y4 Diana Interview 3).

To compensate for this challenge, Diana incorporated the students’ culture into her classroom through culturally-relevant representations of scientists (Y4 Diana Interview 3).

Overall, during Diana's second-year teaching she sought ways to connect with students' religion and culture through in-school and out-of-school experiences. Doing so helped her build relationships with her students and their families, but she still faced challenges while teaching science due to the lack of classroom- and school/district-level resources.

Study Methods

Using qualitative research methods (Miles, Huberman, & Saldaña, 2014) I developed longitudinal case studies (Hesse-Biber & Leavy, 2011; Stake, 2000) of three novice elementary teachers' development of their CKT-S over time and how their knowledge supports science teaching that foregrounds the science practices. The case studies are bounded by the contexts in which the novice elementary teachers work: the practice-based teacher education program and the school contexts. The case studies are not intended to be generalizable, but instead to highlight the "valued particular," through descriptions of "what is important about the case within its own world" (Stake, 2000, p. 439). The studies were used for theory development of novice elementary teachers' trajectories of knowledge development and use. The theories were informed by working hypotheses constructed from comparing the cases to determine the fittingness of the theories (Hesse-Biber & Leavy, 2011). I also created descriptions of the learning opportunities supporting the development of CKT-S in the practice-based teacher education program and the school contexts (Hesse-Biber & Leavy, 2011). This section outlines the data sources, data analyses, limitations, and validity for this study.

Data Sources

The data sources came from the practice-based teacher education program (study years 1 and 2) and the novice elementary teachers' first two years of teaching (study years 3 and 4).

Table 3-2 outlines the total collected data sources across all three teachers for each study year.

For example, in Year 2 there were 14 videorecords of teaching gathered across all three teachers, not 14 videorecords per teacher.

Table 3-2. Overview of total data sources across all three teachers

Data Sources	Frequency (Total data sources per year) ⁸			
	Year 1	Year 2	Year 3	Year 4
<i>Research Question 1: How is novice elementary teachers' content knowledge for teaching science evident in their teaching practice over time?</i>				
Videorecords of teaching and approximations of science teaching	2	14	23	28
Lesson plans for teaching and approximations of science teaching	5	6	3	1
Reflections of teaching and approximations of science teaching		3		
Teacher interviews about teaching and school context (<i>also responds to RQ's 2 and 3</i>)		6	8	9
Baseline assessment: Science lesson plan	3			
Program assessment: Simulated student	2			
<i>Research Questions 2 and 3: What learning opportunities are provided in a practice-based teacher education program and school contexts to support novice elementary teachers' development of their content knowledge for teaching science?</i>				
Course syllabi	2	3		
Course readings	3	10		
Course PowerPoint slides	11	9		
Course assignment sheets	10	2		
Videorecords of course sessions		9		
Teacher surveys			13	12
Interviews with Mentor Teachers		1		
Interviews with Principals			2	1

⁸ There is some variation in the videorecords, lesson plans, and interviews during years three and four, because some teachers submitted more or less than the intended number of lessons and they did not submit lesson plans for every videorecorded lesson. Also, we could not gather all data sources for every teacher during every year.

Videorecords of science teaching and approximations of science teaching.

videorecords address research question one about how the teachers' CKT-S is visible in their instruction. Table 3-3 outlines the specific videorecords, their frequency of occurrence, and when they were recorded. In some instances, I videorecorded the classroom science teaching.

Table 3-3. Overview of the videorecords of science teaching and science teaching approximations for each novice elementary teacher

Science Teaching Approximation	Frequency Per Teacher	Year and Course or Occurrence
Interview with a Student	1 / teacher (available for 2 teachers)	Year 1: Children as Sensemakers I
Simulated Student Interview	1 / teacher (available for 2 teachers)	Year 1: Program Assessment: Simulated Student Interview
Peer Teaching	3 / teacher	Year 2: Elementary Science Methods
Full Scale Science Teaching	1 / teacher	Year 2: Elementary Science Methods
Science Teaching in Classroom	2-9 / teacher	Year 3: First Year Teaching
Science Teaching in Classroom	1 Science Unit / teacher (5-12 lessons / teacher)	Year 4: Second Year Teaching

Year One. Videorecords were collected of the novice elementary teachers' interviews with one or two elementary students during the Children as Sensemakers I course. The first interview was about night and day and the second interview was about sound and how sound is produced. The novice teachers practiced asking probing questions and engaging a student in modeling their ideas to elicit the students' thinking about the scientific phenomena. These assignments should support the novice teachers' understanding about night and day and sound (subject matter knowledge) and their understanding of students' ideas related to these topics, as

well as the instructional moves to elicit students' thinking (pedagogical content knowledge). Videorecords of the teachers' simulated student interviews were coded and analyzed.

Year Two. Videorecords collected during year 2 were from the Elementary Science Methods course and student teaching. The videorecords of science teaching submitted in the Elementary Science Methods course were from the peer teaching approximation and the final assignment. The peer teaching occurred in three segments based on the Engage, Experience, and Explain with evidence framework (Benedict-Chambers, 2014; Kademian & Davis, in press). The novice elementary teachers also taught a full science lesson to elementary students in their field classrooms. During student teaching, the science lesson was either an independent lesson or part of a science unit designed and taught by the novice teacher.

Year Three. The teachers taught and videorecorded lessons during their first year of teaching. The number of science lessons recorded varied from two lessons to nine lessons. The topics of the lessons spanned biological sciences, physical sciences, earth sciences, and engineering.

Year Four. The novice elementary teachers videorecorded each lesson taught within one science unit. The number of science lessons recorded varied from five lessons to 12 lessons. The variation was due to teacher and curriculum materials.

Lesson plans for science teaching and approximations of science teaching. The lesson plans address research question one about how the teachers' CKT-S is visible in their planning. These were collected throughout the teacher education program and in their first two years of teaching (see Table 3-4).

Table 3-4. Overview of the lesson plans for science teaching and approximations of science teaching

Science Teaching Approximation	Frequency Per Teacher	Year and Course or Occurrence
Initial Analysis of Science Lesson Plan	1 / teacher	Baseline Assessment: Initial Analysis of Science Lesson Plan
Lesson Plan Final Exam	1 / teacher	Year 1: Teaching with Curriculum Materials
Full Scale Science Teaching	1 / teacher	Year 2: Elementary Science Methods
Science Teaching in Classroom	2 total (available for 1 teacher)	Year 3: First Year Teaching
Science Teaching in Classroom	19 total (available for 1 teacher)	Year 4: Second Year Teaching

Year One. The novice elementary teachers completed a baseline assessment when they entered the teacher education program. They read a second-grade science lesson on sound and identified strengths and weaknesses of the lesson, potential modifications, and how the activities represented the science content. For the final exam in the Teaching with Curriculum Materials course the novice teachers evaluated and modified learning goals and assessments in a second-grade buoyancy lesson plan. The final exam serves as a comparison to the initial baseline assessment.

Year Two. In Elementary Science Methods, the novice elementary teachers submitted lesson plans with their peer teaching approximations and the FSST assignment. They used a science-specific Instructional Planning Template (see Appendix A) that included writing a scientific explanation answering an investigation question and instructional sequences for each portion of the EEE framework. Lesson plans were also collected for science lessons taught during the student teaching semester.

Year Three. Lesson plans were collected during the novice elementary teachers' first year of teaching for the science lessons they taught. Only two lesson plans were submitted by Claudia. Harry and Diana did not submit any lesson plans.

Year Four. Lesson plans were collected during the novice elementary teachers' second year of teaching for the science lessons they taught. Only Claudia submitted lesson plans for her unit. There were 19 total lesson plans.

Reflections of videorecords for course assignments. The written reflections provide opportunities to “see” the novice teachers’ thinking – an assumed, yet invisible aspect of teaching – which addresses research question one about the teachers’ CKT-S. Reflections were collected from the Children as Sensemakers I and Elementary Science Methods course assignments. The written reflections from the Children as Sensemakers I course are about the teachers’ interviews with individual students.

The written reflections completed in the Elementary Science Methods course were part of the FSST assignment and focused on the novice teachers’ thoughts about science teaching. They were often about how well the teachers engaged their students in the science practices.

Interviews about science teaching and school environment. The novice elementary teachers participated in semi-structured interviews (Hesse-Biber & Leavy, 2011) during years 2, 3, and 4 (see Table 3-5). The interviews included pre-determined questions about their experiences and thinking related to science teaching. The questions also asked about the novice teachers’ feelings toward science teaching and their experiences in the teacher education program (mainly in year 2) and their school context (only in years 3 and 4). All interviews were audio recorded and transcribed. The interviews address research questions 1, 2, and 3 regarding

the teachers' CKT-S and learning opportunities in the teacher education program and the school contexts.

Table 3-5. Overview of the interviews about science teaching, the teacher education program, and the school context

Interview	Frequency Per Teacher	Year and Interview Focus
Post-Science Methods Interview	1	Year 2: Experiences in Elementary Science Methods and Teacher Education Program
Post-Student Teaching	1	Year 2: Experiences in Student Teaching and Teacher Education Program
First Year Science Teaching	2-3	Year 3: Science Teaching and School Context
Second Year Science Teaching	3	Year 4: Science Teaching and School Context

Year Two. The novice elementary teachers were interviewed twice about their science teaching experiences and experiences in the teacher education program. The first interview was completed after the Elementary Science Methods course and the questions related to their experiences during the course (see Appendix B for the Post-Science Methods Interview Protocol). The second interview was conducted toward the end of the student teaching experience and asked questions about the novice teachers' science teaching during student teaching (see Appendix C for the Post-Student Teaching Interview Protocol).

Year Three. The interviews conducted during the novice teachers' first year teaching occurred two to three times and asked about their views and experiences teaching science. The interview protocols included stimulated recall questions (Calderhead, 1981; Schachter & Freeman, 2015) where segments of video of the teachers' instruction were replayed and questions asked about their in-the-moment thinking regarding their use of (a) scientific

representations, (b) scientific and everyday language, (c) real-world examples, and (d) students' ideas shared during the science lesson (see Appendix D for a sample interview protocol). The video segments to be replayed were identified by a researcher (typically me). Other semi-structured interview questions asked broader questions related to the novice teachers' science instruction.

Year Four. The interviews conducted during the novice teachers' second year teaching occurred three times during and after their teaching of a science unit. The first two interviews included stimulated recall questions, similar to study year 3, asking about the novice teachers' in-the-moment thinking (Calderhead, 1981; Schachter & Freeman, 2015) (see Appendix E for a sample interview protocol). The final interview was a semi-structured interview (Hesse-Biber & Leavy, 2011) asking about the school context including (a) resources in their schools, (b) science-related professional development opportunities, (c) the curriculum materials, (d) experiences working with fellow teachers and/or the principal, (e) their perceptions of the school and district's views of science teaching and learning, and (f) how they think their science teaching has changed over the past four years (see Appendix F for a sample interview protocol).

Course Syllabi, Readings, PowerPoint Slides, and Assignment Sheets. I analyzed course-related documents to describe the opportunities to learn CKT-S (research question two). These included syllabi, PowerPoint slides, and assignment sheets for Children as Sensemakers I, Teaching with Curriculum Materials, and the Elementary Science Methods course. It also included readings from the Children as Sensemakers I course and the Elementary Science Methods course. There were no readings assigned in the Teaching with Curriculum Materials course.

Videorecords of Elementary Science Methods course sessions. To characterize the learning opportunities for developing teachers' CKT-S (research question two), videorecords of the nine class sessions in the Elementary Science Methods course were analyzed. The course activities were analyzed for opportunities provided that they supported knowledge development for teaching investigation-based science lessons.

Year 1 program assessment: Simulated student interviews. At the end of their first year in the program, some novice teachers took a program assessment related to science teaching: simulated student interviews (Dotger, Harris, & Hansel, 2008). It assessed how the novice teachers began to think about conservation of mass and how to support a "student" (role played by a teacher educator) in analyzing data to make sense of conservation of mass (Arias & Davis, 2017b). The simulated student interviews were videorecorded and included written work by the novice teachers. These were analyzed for whom data exists to inform the study of the teachers' CKT-S (research questions one) prior to the Elementary Science Methods course.

Teacher surveys. Brief teacher surveys asked questions about the frequency of the novice elementary teachers' science teaching and contextual influences on their science teaching (e.g., science materials, curriculum materials). The questions were developed by the ATTEST research project and were modified from the Banilower and colleagues (2013) survey conducted with elementary teachers across the United States. The modifications were made due to length and applicability (see Appendix G for sample teacher survey questions). The surveys were administered during study years 3 and 4 and informed the development of targeted questions asked during the third interview conducted in study years 3 and 4 (see the section on interviews above). The surveys also addressed research questions one and three.

Interviews with mentor teachers and principals. The mentor teachers (year 2) (see Appendix H) and the principals (years 3 and 4) (see Appendix I) were interviewed about their views and the district's views of science teaching and learning in order to identify learning opportunities in the school environments (research question three).

Data Storage. To prevent unauthorized access of project data, all data was stored in designated files on MBox, as well as on a password-protected external hard drive. A document containing the real names and contact information of the participants was stored in a separate MBox folder and on a different, password-protected hard drive. This was to maintain anonymity and confidentiality of the participants, as well as avoid concerns of data loss.

Limitations of the Study

While overall a strength, the longitudinal nature of the study created certain limitations. One limitation was the type of data collected in year 3 compared with year 4. In year 3, the novice teachers submitted videorecords of approximately three science lessons across the year. In comparison, the novice teachers submitted videorecords of each lesson in one science unit during year 4. The units occurred toward the end of year 4 compared with the data collection across the entire school year in year 3. A reason for this change was due to the piecemeal videorecords received in year 3. For example, Harry videorecorded the data collection portion of a science lesson from one day and did not videorecord the sensemaking discussion that occurred on another day. By having teachers videorecord all lessons in a single unit, all parts of science lessons were recorded – including some lessons that were not investigation-based science lessons (e.g., science lessons using texts). One way I attended to this discrepancy is that I coded and analyzed similar types of lessons to those collected during year 3 (investigation-based and

emphasizing sensemaking). Also, Claudia videorecorded the science unit in year 4 that she taught a lesson from in year 3, which allowed me to see some consistency across the two years.

Another limitation is the challenge in following novice teachers during their first few years of teaching. For example, Diana worked as a long-term substitute teacher in multiple classrooms during year 3, but was in her own classroom during year 4. Each case can have inconsistencies when considering the influences of the school context (or possibly multiple, changing contexts) on the teachers' practice. They do, however, represent deviant cases (Flyvbjerg, 2006) that provide unique insights into the contexts and learning opportunities (or lack thereof) in different school contexts that are not uncommon for novice elementary teachers.

Data Coding and Analysis

Using qualitative case study methodology, I constructed case studies for each teacher that inform trajectories of their knowledge in and for science teaching (Ragin, 1992; Stake, 2000). I used analytical questions to guide the analyses of data (see Table 3-6) and discuss hypotheses of potential findings and how validity was determined.

Table 3-6. Main research questions with associated analytical questions

<i>1. How is novice elementary teachers' content knowledge for teaching science evident in their teaching practice over time?</i>
1a. How is novice elementary teachers' CKT-S evident in their science instruction? How does their CKT-S change over time?
1b. How is novice elementary teachers' CKT-S represented in their lesson planning? How does their CKT-S change over time?
1c. How is novice elementary teachers' CKT-S represented in their reflections on their science teaching? How does their CKT-S change over time?
1d. What do the novice elementary teachers know about one key science topic, ecosystems, prior to taking the Elementary Science Methods course?
1e. What do the novice elementary teachers know about one key science practice, scientific argumentation, prior to taking the Elementary Science Methods course?
<i>2. What learning opportunities are provided in a practice-based teacher education program to support novice elementary teachers' development of their content knowledge for teaching science?</i>
2a. What learning opportunities may support novice elementary teachers' development of their CKT-S in the Children as Sensemakers I course?
2b. What learning opportunities may support novice elementary teachers' development of their CKT-S in the Teaching with Curriculum Materials course?
2c. What learning opportunities may support novice elementary teachers' development of their CKT-S in the Elementary Science Methods course?
<i>3. What learning opportunities do the school contexts provide to support novice elementary teachers' development of their content knowledge for teaching science?</i>
3a. How do the mentor teachers and principals discuss science teaching and learning and what could this mean for the novice elementary teachers' development of their CKT-S?
3b. How do the novice teachers discuss the influences of the school and district resources on their science teaching and knowledge development?
<i>4. How do the learning opportunities for developing CKT-S in the teacher education program and the school contexts compare to the novice elementary teachers' knowledge in and for their teaching?</i>

Question 1a. How is novice elementary teachers' CKT-S represented in their science instruction? How does their CKT-S change over time?

Question 1b. How is novice elementary teachers' CKT-S represented in their lesson planning? How does their CKT-S change over time?

Question 1c. How is novice elementary teachers' CKT-S represented in their reflections on their science teaching? How does their CKT-S change over time?⁹

Coding for the novice elementary teachers' CKT-S involved coding the videos of their instruction, as well as their lesson plans and reflections on their teaching. The videos were divided into two minute segments (Borko, Jacobs, Eiteljorg, & Pittman, 2008) and their talk in each two minute segment was coded. The lesson plans, written reflections, and transcribed interviews (spoken reflections) were divided by idea unit (Stemler, 2001) and each idea unit was coded. I drew on initial work with this coding method (Bismack et al., 2017a; Bismack, Davis, & Palincsar, 2017b) to code each two minute segment and idea unit in three phases: (1) broad a priori coding for evidence of each sub-domain of CKT-S (see Table 3-7), (2) a priori coding of the science practices that the teacher mentions, and (3) a priori coding of the quality of the teachers' CKT-S (see Appendices J-O for sample codebooks for the second and third phases) (Miles et al., 2014). All coding was done in Atlas.ti – a qualitative analysis computer program.

⁹ The same coding method and codebooks were used to code the videorecords, lesson plans, written reflections, and interviews. For this reason, I include all three analytic questions together and I describe the coding and analyses of all of these data sources in this one section.

Table 3-7. Phase 1 Coding of Novice Teachers' Content Knowledge for Teaching Science

Code	Description
Core Content Knowledge: Science Concepts	Novice teacher makes a statement that draws on their knowledge about a science topic
Core Content Knowledge: Science Practices	Novice teacher makes a statement that draws on their knowledge about science practices
Horizon Content Knowledge	Novice teacher makes a statement that draws on their knowledge of how the current science topic builds on what was previously learned or will support science learning in the future
Knowledge of Content and Students	Novice teacher makes a statement that draws on their knowledge of students' alternative ideas, challenges, interests, or cultural influences related to the science topic
Knowledge of Content and Curriculum	Novice teacher draws on their knowledge of the science curriculum materials, standards, or assessments
Knowledge of connections of science to non-science disciplines	Novice teacher makes a statement that draws on their knowledge of how the science topic relates to non-science disciplines (e.g., mathematics)
Knowledge of applications of science	Novice teacher makes a statement that draws on their knowledge of how the current science topic applies to other phenomena or social issues not directly related to the current lesson

Drawing from the literature (Ball et al., 2008; Davis & Petish, 2005; Kloser, 2014; Nixon et al., 2019; Shulman, 1986, 1987), the a priori codes represent teachers' understanding of the science concepts, science practices, horizon content knowledge, knowledge of content and students, knowledge of the connections between science and non-science disciplines, and knowledge of the applications of science. When coding I did not initially call attention to the teachers' knowledge of content and teaching, because this was more evident during the third phase of coding when coding for quality of teachers' knowledge of the science practices. During

the third phase of coding, I marked in Atlas.ti when teachers' knowledge of content and teaching of the science practices was evident in the two-minute segments and idea units. This allowed me to analyze teachers' knowledge of content and students retroactively. Lastly, I did not code for the teachers' specialized content knowledge due to the subtle nature of this sub-domain (Ball & Bass, 2000, 2003; Johnson & Cotterman, 2015; Thames, 2008).

During the second phase of coding, I identified which science practices were foregrounded. This guided what segments were coded in phase three. The final phase of coding investigated the quality of *how* the novice elementary teachers' CKT-S appears in their science instruction. A priori codes of the dimensions of the teachers' CCK and KCT of the science practices were developed from the literature on the science practices (Arias & Davis, 2016, 2017a; Eberbach & Crowley, 2009; Lee & Butler, 2003; McNeill, 2009; National Research Council, 2012; NGSS Lead States, 2013; Zangori et al., 2013; Zembal-Saul, 2009). Rubrics were developed for all science practices, except asking scientific questions, mathematical and computational thinking, and obtaining, evaluating, and communicating information. Rubrics were not developed for those science practices due to their minimal use in the teachers' science teaching, which is similar to other elementary teachers (Plumley, 2019). The rubrics identified dimensions of the teachers' CCK and KCT for each science practice (see Appendix J).

For checking the reliability of the coding scheme, a second researcher conducted interrater reliability on over 10% of the data during each round of coding. First, we completed interrater reliability on identifying idea units in the data, which involved a second researcher coding 26% of the data and achieving 87% reliability on identifying idea units. Second, we conducted interrater reliability to determine the first round of coding for those idea units. We reached 85% positive agreement for coding segments for evidence of the teachers' knowledge of

each sub-domain of CKT-S with all disagreements resolved through discussion. Third, we conducted interrater reliability on the quality of the teachers' knowledge for each of the science practices. Table 3-8 outlines the range of interrater reliability scores for each science practice with the complete interrater reliability scores in Appendix K. We found positive and negative agreement due to the relatively small number of segments coded as having evidence of the teachers' knowledge of the science practices. The ranges indicate the interrater reliability scores for the dimensions of each science practice. I determined that a score of 70% and above is considered acceptable agreement with a score of 90% and above considered to be exceptional agreement (Campbell & Evans, 2000; Fahy, 2001; Kurasaki, 2000).

Table 3-8. Ranges of Interrater Reliability Scores for Round 3 Coding of Teachers' Quality of Knowledge of the Science Practices

Dimensions of Science Practices	Ranges of % Positive Agreement	Ranges of % Negative Agreement
Scientific Investigations	78-100%	78-90%
Scientific Predictions	86-100%	83-93%
Scientific Observations	79-100%	73-96%
Analyzing and Interpreting Data	90-100%	74-96%
Scientific Explanations and Arguments	70-100%	70-100%
Scientific Modeling	79-100%	70-100%

To analyze the data for evidence of the teachers' knowledge of the sub-domains of CKT-S, I developed a table outlining their knowledge during each year in the study. The table included the frequency of the teachers' knowledge appearing in their teaching practice, as well as the percentage of evidence of their knowledge for each sub-domain (see Table 4-1). I then created

graphs of the percentage of the teachers' knowledge evident in their teaching practice for each sub-domain. The table and graphs informed the written descriptions of the teachers' knowledge. All descriptions were supported with quotes from the teachers' instruction, lesson plans, reflections, and interviews.

To analyze the data for quality of the teachers' knowledge of the science practices (CCK: Science Practices) and knowledge of how to engage students in the science practices (KCT), I developed tables outlining the mean scores of each teachers' understanding of each science practice (see Table 4-2 for an example). I used those tables to write descriptions of the teachers' understanding of the science practices including descriptions of how they understood each dimension of the science practices.

Lastly, using the mean scores of the teachers' understanding of each dimension of the science practices, I developed (a) one graph comparing the dimensions of CCK for all science practices (see Figure 4-10), and (b) another graph comparing the dimensions of KCT for all science practices (see Figures 4-11). Using those graphs, I wrote descriptions of how the understanding of the dimensions compared with one another. The comparisons allowed me to identify dimensions of the science practices that could support novice elementary teachers' "science practice readiness" for understanding the science practices and understanding how to engage students in them (see Chapters 4 and 7).

Question 2a. What learning opportunities may support novice elementary teachers' development of their CKT-S in the Children as Sensemakers I course?

Question 2b. What learning opportunities may support novice elementary teachers' development of their CKT-S in the Teaching with Curriculum Materials course?

Question 2c. What learning opportunities may support novice elementary teachers' development of their CKT-S in the Elementary Science Methods course?

Question 3a. How do the novice elementary teachers discuss the opportunities to support their development of their CKT-S in their teaching experiences?

Question 3b. How do the mentor teachers and principals discuss science teaching and learning and what could this mean for opportunities supporting the novice elementary teachers' development of their CKT-S?¹⁰

To code the data for the opportunities to learn, the interviews, teacher surveys, course syllabi, assignment sheets, PowerPoint slides, readings, and videos of class sessions were each divided into idea units based on when the text or instance shifted content (Stemler, 2001). There was a total of 2,515 idea units across the four years. Each idea unit represented an opportunity to learn CKT-S. Due to the type of data sources used, there was no distinction as to the value of one opportunity to learn over another. For example, one opportunity might be sentences on a PowerPoint slide and another opportunity might be the mention of a professional development experience by a novice teacher during an interview. Because the data do not indicate value or time spent on different opportunities, I instead investigated what knowledge sub-domains the opportunities supported during the four years.

¹⁰ The same coding method and codebooks were used to code the videorecords, lesson plans, written reflections, and interviews. For this reason, I include all three analytic questions together and I describe the coding and analyses of all of these data sources in this one section.

After identifying each opportunity, they were coded based on which knowledge sub-domain(s) the opportunities supported. Since an opportunity might support multiple sub-domains, some opportunities were given multiple codes. I conducted a second round of coding on the opportunities potentially supporting teachers' knowledge of content and teaching, students, and curriculum due to their greater frequency and variability. The first round of coding used a priori coding (Stemler, 2001) that identified which sub-domains of CKT-S the opportunities supported (see codebook in Table 3-9).

Table 3-9. Codebook for Opportunities to Learn Sub-Domains of CKT-S

Opportunities Supporting the Specific Sub-Domains	Description	Example
CCK: Concepts	Learning opportunities that support teachers' understanding of science concepts	CaSM Week 1 PPT: What is the scientific explanation for how we have the day/night cycle?
CCK: Practices	Learning opportunities that support teachers' understanding of science practices	ESM Week 4 PPT: Scientific observations and data are used as evidence in scientific explanations
HCK	Learning opportunities that support teachers' knowledge of how the science concepts or practices develop over time	Instructional Planning Considerations: Does the lesson connect in a sensible sequence to other lessons within the unit, to develop a coherent storyline?
KCT	Learning opportunities that support teachers' knowledge of how to teach science	CaSM Syllabus: Facilitate student sense-making using text and physical modeling
KCS	Learning opportunities that support teachers' knowledge of their students and science	CaSM Assignment 3: For the day/night explanation, how does your student's final explanation <i>compare and contrast</i> with his or her initial explanation?
KCC	Learning opportunities that support teachers' knowledge of science curriculum, standards, and assessments	TwCM Syllabus: Curriculum materials can be seen as a set of instructions for teaching
Knowledge of Connection of Science to Non-Science Disciplines	Learning opportunities that support teachers' knowledge of how the science concepts and/or practices relate to non-science disciplines	ESM Reading: Communicating in these kinds of complex ways...can be extended to other disciplines
Knowledge of Applications of Science	Learning opportunities that support teachers' knowledge of how science has broader implications beyond the lesson	ESM Week 1 PPT: Apply knowledge to new problems or questions

To check the reliability of the coding, I worked with a second researcher to conduct interrater reliability on over 10% of the idea units. For sub-domains with a reasonable number of codes (at least 30% of the idea units coded as the sub-domain), I calculated Cohen's Kappa to account for the potential of agreement due to chance (Cohen, 1960). We achieved a minimum agreement of $\kappa = .8$ (McHugh, 2012), the level at which "substantial" agreement is indicated. For the others, we calculated positive and negative agreement with all disagreements resolved through discussion. Similar to the interrater reliability conducted about the teachers' CKT-S, a score of 70% and above is considered acceptable agreement with a score of 90% and above considered to be exceptional agreement (Campbell & Evans, 2000; Fahy, 2001; Kurasaki, 2000) when determining percent positive and negative agreement. Table 3-10 includes the interrater reliability for opportunities that support the sub-domains.

Table 3-10. Interrater Reliability for Round 1 Coding of Opportunities Supporting Sub-domains of CKT-S

OTL Sub-Domain	Kappa (κ)	% Positive Agreement	% Negative Agreement
CCK: Science Concepts	-	70%	90%
CCK: Science Practices	-	80%	100%
HCK	-	100%	100%
KCT	.81	90%	92%
KCS	.88	90%	98%
KCC	.83	81%	98%
Knowledge of Connection to Non-Science Disciplines	-	-	99%
Application of CK	-	-	100%

The second round of coding used emergent codes to identify how the opportunities supported the knowledge of content and teaching, students, and curriculum (Charmaz, 2004) due to the prevalence of those opportunities compared to the opportunities supporting the other sub-domains. Sample codes for opportunities that supported aspects of KCT included supporting teachers' knowledge of how to facilitate discourse in the classroom; knowledge of how science lessons can be divided into the Engage, Experience, and Explain sections (per an instructional framework used in the science methods class); and knowledge of how to support students in constructing scientific explanations, among others. Sample codes for opportunities that supported aspects of KCS included supporting teachers' knowledge of students' alternative ideas and challenges with science topics and practices and the knowledge of the influences of students' cultures, race, gender, nationality, and identity on science teaching and learning, among others. Sample codes for opportunities that supported aspects of KCC included supporting teachers' knowledge of curriculum materials, knowledge of learning goals, and knowledge of how to write learning goals, among others (see Appendix L for the KCT, KCS, and KCC codebooks).

To determine reliability of the second round of coding, I worked with a second researcher to calculate positive and negative agreement for 10% of the idea units coded as supporting KCT, KCS, and KCC. For space constraints, I only include ranges of interrater reliability scores in Table 3-11 with the complete interrater reliability scores reported in Appendix M.

Table 3-11. Ranges of Interrater Reliability Scores for Second Round of Coding Opportunities to Learn Aspects of KCT, KCS, KCC

OTL Aspects of Sub-Domain	Ranges of % Positive Agreement	Ranges of % Negative Agreement
KCT	78-100%	94-100%
KCS	89-98%	87-100%
KCC	93-98%	95-100%

After completing both rounds of coding, I identified patterns in how the opportunities to learn the sub-domains of CKT-S varied across the different experiences within the teacher education program and the teaching experiences. The patterns included

- (a) the frequency of opportunities supporting CKT-S in different experiences (e.g., the greater number of opportunities in the Elementary Science Methods course),
- (b) the percentage of opportunities supporting CKT-S in different experiences (e.g., Teaching with Curriculum Materials focused on supporting the teachers' KCC), and
- (c) the different ways the opportunities potentially supported the teachers' knowledge of the sub-domains (e.g., hearing students' questions and alternative ideas during teaching experiences led to opportunities that supported teachers' knowledge of science concepts).

I discuss these analyses in Chapter 4.

Question 4. How do the learning opportunities for developing CKT-S in the teacher education program and the school contexts compare to the novice elementary teachers' knowledge in and for their teaching practice?

The trajectories of the teachers' CKT-S and opportunities to learn were developed based on comparative analyses of the findings in chapters 4 and 5. To do this, I developed figures that represent the percentages of the teachers' knowledge and the opportunities to learn (see Figure 6-

1). The figures reflect the CKT-S framework included in Figure 2-3. I also compared the findings of the opportunities to learn supporting core content knowledge and knowledge of content and teaching about the science practices (see Tables 6-1, 6-2, and 6-3). The tables were developed for each teacher, because their knowledge was dependent on their varied teaching experiences.

I then wrote cases of each teacher describing their trajectories of knowledge development compared with their opportunities to learn. To explain in greater depth the relationships between the opportunities to learn and each teacher's CKT-S, I discussed strengths and limitations of the opportunities to learn and CKT-S. The strengths and limitations were identified by referring to the teachers' own stated strengths and limitations discussed during interviews. I then corroborated their self-identified strengths and limitations with the findings from chapters 4 and 5. I then wrote vignettes for each case that demonstrated their strength and discussed how their CKT-S was evident in the vignette. I compared the identified knowledge with the opportunities to learn throughout their teaching. Each case ends with a description of each teacher's self-identified limitation and how their limitation compared with the opportunities to learn that supported (or not) the knowledge sub-domain. Lastly, I synthesized the similarities and differences of the teachers' knowledge and opportunities to learn across the three trajectories. I discuss these analyses in chapter 6.

Trustworthiness of Findings

Because my intent is to characterize novice elementary teachers' knowledge in and for science teaching, I intentionally view elementary science teaching as complex and integrated with teaching practice and school environments. Though my coding was fine grained when looking at individual data sources (Dyson & Genishi, 2005), I purposefully collected data from

multiple sources and looked across those sources to develop a larger, more complete picture of how the novice teachers develop their content knowledge for teaching science as represented in their science teaching (Erickson, 1986). I used multiple data sources for purposeful triangulation, thereby increasing the validity of my claims (Erickson, 1986). As discussed above, I also conducted interrater reliability with a second researcher. Lastly, the reflections and interviews, particularly questions in the final interview, were used as a form of member checking to determine whether my findings about the teachers' knowledge were similar to how the novice teachers think about their teaching (Calderhead, 1981; Hesse-Biber & Leavy, 2011; Schachter & Freeman, 2015).

I do not intend to generalize the findings from each of the teacher cases to all novice elementary teachers, but instead characterize potential trajectories of knowledge development and learning opportunities that novice elementary teachers can take if in similar circumstances (Erickson, 1986; Flyvbjerg, 2006). Due to the small number of teachers in this study, I used multiple data sources to provide validity to the claims I make and to deepen the case studies of each teacher. I characterize how each case develops knowledge over time and consider what that means for developing learning opportunities within teacher education and school contexts for supporting other novice elementary teachers in their science teaching practices.

The following chapters outline the findings from these analyses. Chapter 4 characterizes the opportunities to learn across the four years that supported the novice elementary teachers' development of their CKT-S. Chapter 5 characterizes the teachers' CKT-S across the four years and the quality of their understanding of the science practices. Chapter 6 describes the trajectories of the novice elementary teachers' CKT-S in relation to the opportunities to learn. Lastly, chapter 7 connects the findings from the current study to the literature on science

teachers' knowledge and opportunities to learn. I articulate how the findings support and extend the literature on what it means for novice elementary teachers to develop as well-started beginners and how to support their development across contexts. I also include implications for further teacher supports within practice-based teacher education and school contexts, as well as implications for further research on elementary teachers' CKT-S and opportunities to learn.

Chapter 4 Opportunities to Learn CKT-S During Early Years of Teacher Development

This chapter seeks to answer the research questions: *What learning opportunities are provided in a practice-based teacher education program to support novice elementary teachers' development of their content knowledge for teaching science?* and *What learning opportunities do the school environments provide to support novice elementary teachers' development of their content knowledge for teaching science?* In response to the first research question, I coded and analyzed the course syllabi, PowerPoint slides, readings, assignments, and videorecords of class sessions in the Elementary Science Methods course. In response to the second research question, the teacher surveys, teacher interviews, mentor teacher interviews, and principal interviews were all coded and analyzed. Through my analyses, I characterize variation in how the opportunities potentially supported the novice elementary teachers' development of sub-domains of their content knowledge for teaching science and how opportunities supporting some aspects of knowledge can lead to opportunities to support other aspects of knowledge.

Overall, the novice elementary teachers had more opportunities to develop their pedagogical content knowledge compared to their subject matter knowledge during their early years of learning how to teach. Given that the purpose of the teacher education program is to orient novice teachers to the knowledge and practices of teaching content to students, it is not surprising that the program foregrounded supporting teachers' pedagogical content knowledge. Supporting pedagogical content knowledge entails supporting novice teachers' knowledge of

content and teaching, knowledge of content and students, and knowledge of content and curriculum (Ball et al., 2008; Shulman, 1986).

To a lesser extent, the opportunities to learn in the teacher education program also supported teachers' subject matter knowledge, which included their core content knowledge of science concepts, core content knowledge of science practices, and their horizon content knowledge (Ball et al., 2008; Nixon et al., 2019).¹¹ The novice teachers' opportunities to develop their pedagogical content knowledge (e.g., make sense of students' alternative ideas) led to other opportunities to develop their core content knowledge of science concepts. Also, few opportunities supported the teachers' knowledge of the connections of science to non-science disciplines (Shulman, 1987) and knowledge of the applications of science.

To illustrate the variation in total opportunities to learn across experiences, Figures 4-1 and 4-2 include the frequencies of the total opportunities to learn for each experience and each sub-domain. The shaded regions represent the frequencies of opportunities provided in each experience. The bars represent the frequency of opportunities in each experience that supported the teachers' development of the sub-domains of content knowledge for teaching science. For example, in the Children as Sensemakers course (see Figure 4-1) there were a total of 381 opportunities to learn and of those total opportunities 248 supported the teachers' KCT (green bar). Figure 4-2 provides the same type of representation for the opportunities to learn in the novice elementary teachers' first two years of teaching.

¹¹ The novice teachers had other opportunities to learn core content knowledge outside of the professional coursework of the teacher education program, which was the focus of my study.

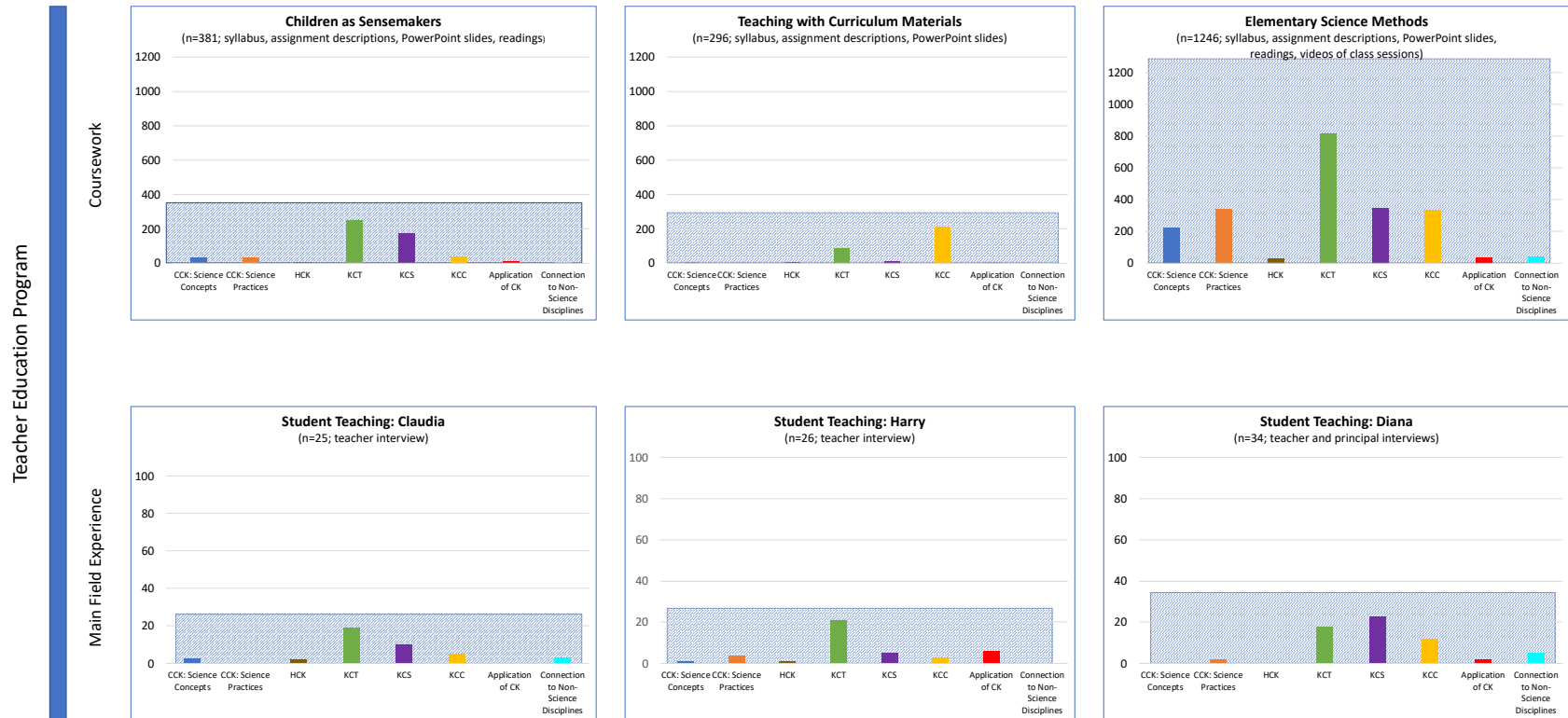


Figure 4-1. Opportunities to learn content knowledge for teaching science during the teacher education program (n=2008)
(Shaded regions indicate the number of coded idea units for each experience. Bars indicate the frequency of idea units coded as supporting specific sub-domains.)

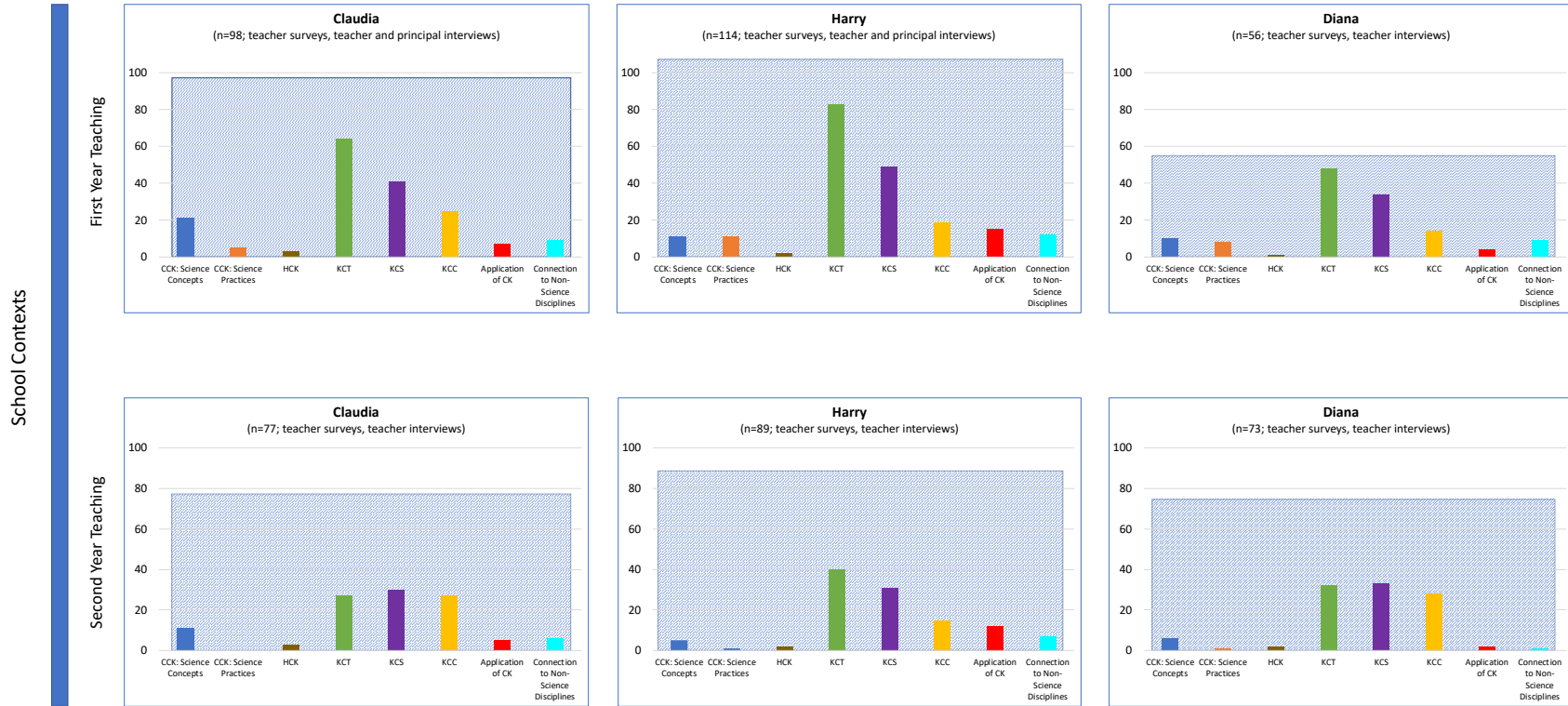


Figure 4-2. Opportunities to learn content knowledge for teaching science during the first two years of teaching (n=507).

(Shaded regions indicate the number of coded idea units for each experience. Bars indicate the frequency of idea units coded as supporting specific sub-domains.)

The opportunities varied by frequency and by experience across the early years of the teachers' development. Across all of the experiences, the Elementary Science Methods course provided the majority of the opportunities to learn CKT-S. This is not surprising as the purpose of the course is "to prepare [novice teachers] to foster science learning in elementary school students" (Y2 ESM Syllabus). Other opportunities in the teacher education program and beyond either supported or built on the experiences provided in that course. For example, the opportunities focused on planning for science teaching in the Elementary Science Methods course were supported by prior experiences in the Teaching with Curriculum Materials course on how to evaluate and modify learning goals. Similarly, opportunities in the teaching experiences that supported teachers' knowledge of the standards built on similar opportunities in the Elementary Science Methods course focusing on the standards.

The following sections provide illustrative examples of how the opportunities supported the teachers' development of each sub-domain of CKT-S. Within each section, I begin with an overview of how the opportunities supported the particular sub-domain across all four years. I continue with examples of how the opportunities supported the knowledge sub-domain in the courses in the teacher education program and the teacher experiences. When evident, I describe nuances of how the opportunities in different experiences supported sub-domains in different ways. Finally, I end the chapter with an overview articulating the cyclical nature of how opportunities supporting pedagogical content knowledge can lead to opportunities supporting subject matter knowledge.

Opportunities to Learn Subject Matter Knowledge

Based on the data studied, there were few opportunities in the teacher education program and school contexts that supported the novice teachers' development of their subject matter

knowledge. Most of the opportunities in the teacher education program occurred during the Elementary Science Methods course with a few in the Children as Sensemakers course. The opportunities in the teaching experiences varied by teacher and the instructional needs of each school context. I discuss the variations particular to each sub-domain below.

Opportunities Supporting Teachers' Core Content Knowledge for Science Concepts

Core content knowledge for science concepts was supported mainly in some teaching experiences (ranging between 6% to 21% of the opportunities coded within the first and second years of teaching) and the Elementary Science Methods course (18% of total coded opportunities within the course) with a few opportunities in the Children as Sensemakers course (8% of total) (see Table 4-1). These experiences provided some opportunities that supported novice teachers in developing their understanding of particular science concepts.

Table 4-1. Opportunities to Learn in Each Experience that Supported Core Content Knowledge for Science Concepts (of the total coded opportunities to learn in each experience)

Experiences	Frequency and percentage
Y1: Children as Sensemakers	30/381 (8%)
Y1: Teaching with Curriculum Materials	5/296 (2%)
Y2: Elementary Science Methods	227/1246 (18%)
Y2: Student Teaching: <i>Claudia</i>	3/25 (12%)
Y2: Student Teaching: <i>Harry</i>	1/26 (4%)
Y2: Student Teaching: <i>Diana</i>	0/34 (0%)
Y3: First Year Teaching: <i>Claudia</i>	21/98 (21%)
Y3: First Year Teaching: <i>Harry</i>	11/114 (10%)
Y3: First Year Teaching: <i>Diana</i>	10/56 (18%)
Y4: Second Year Teaching: <i>Claudia</i>	11/77 (14%)
Y4: Second Year Teaching: <i>Harry</i>	5/89 (6%)
Y4: Second Year Teaching: <i>Diana</i>	6/73 (8%)

Each opportunity was typically specific to a particular assignment, activity, or lesson taught in the classroom. For example, in the Children as Sensemakers course the opportunities that supported the teachers' core content knowledge of science concepts focused on their understanding of day and night and sound, which were the focus of the interviews with children. Similarly, the opportunities in the Elementary Science Methods course were particular to activities where the need for understanding specific science concepts prefaced the novice teachers' abilities to engage in particular science teaching practices. For example, the course instructor explained a food web diagram outlining why hawk populations would decrease stating,

So in the end, there are no sparrows that the hawks eat, less squirrels that the hawks eat, and so a decrease in hawk populations (Y2 ESM Week 8 Video).

The explanation of the food web diagram provided an opportunity to support the teachers' core content knowledge of science concepts so they could read and evaluate students' science explanations of that same science concept. In these examples, the opportunities were specific to the assignment and activity in the courses.

In a similar way, the opportunities in the teaching experiences that supported the teachers' core content knowledge of science concepts were specific to the topics of the science lessons being taught. Usually the need to pursue these opportunities were prompted either by the concepts in the standards, the teachers' own planning for their science lessons, or by students' potential or stated alternative ideas. For example, Diana mentioned that, "looking at the standards...[and] the information necessary to answer that or to meet that kind of expectation" was a trigger for her to seek out resources that would support her knowledge development (Y4 Diana Interview 1).

Another trigger was students' potential or stated alternative ideas that caused the novice teachers to seek out opportunities to support their knowledge development. Harry highlighted this when he mentioned that,

Starting with an inquiry chart for the units is really helpful so that I can kind of understand what [students] know already and then maybe some misconceptions. There are some things they say that I'm like, "Yeah, that's true." Some things they say where I know that's not true. And some things they say, I'm like, "Well, I'm actually not sure if that's true." So, that kind of gave me a nice starting point to focus my research and to be able to answer those questions (Y4 Harry Interview 3).

Planning and reading through the curriculum materials also provided opportunities for the novice teachers to develop their science knowledge. As Claudia mentioned,

I do try to do my own research. And I'll try to read the teacher background and the curriculum materials. And I'll read articles and things online as I realize I need to know more (Y4 Claudia Interview 2).

The novice elementary teachers pursued further opportunities to learn about the science concepts based on their interactions with standards, students, and curriculum materials.

Opportunities Supporting Teachers' Core Content Knowledge for Science Practices

Overall, core content knowledge of science practices was the most supported sub-domain of subject matter knowledge in the teacher education program. In particular, the opportunities tended to be mainly situated within the Elementary Science Methods course (28% of the total opportunities coded in the course) with some extending into particular teachers' teaching experiences (see Table 4-2).

Table 4-2. Opportunities to learn in each experience that supported core content knowledge for science practices (of the total coded opportunities to learn in each experience)

Experiences	Frequency and percentage
Y1: Children as Sensemakers	33/381 (9%)
Y1: Teaching with Curriculum Materials	4/296 (1%)
Y2: Elementary Science Methods	343/1246 (28%)
Y2: Student Teaching: <i>Claudia</i>	0/25 (0%)
Y2: Student Teaching: <i>Harry</i>	4/26 (19%)
Y2: Student Teaching: <i>Diana</i>	6/34 (3%)
Y3: First Year Teaching: <i>Claudia</i>	5/98 (5%)
Y3: First Year Teaching: <i>Harry</i>	11/114 (10%)
Y3: First Year Teaching: <i>Diana</i>	8/56 (14%)
Y4: Second Year Teaching: <i>Claudia</i>	0/77 (0%)
Y4: Second Year Teaching: <i>Harry</i>	1/89 (1%)
Y4: Second Year Teaching: <i>Diana</i>	1/73 (1%)

The Elementary Science Methods course provided a range of opportunities which included course readings, class activities, and assignments that focused on teaching lessons engaging students in the science practices. One of the course readings was the NGSS Appendix F, which explains each science practice and expectations for students (NGSS Lead States, 2013, Appendix F). Science practices were also explained during class sessions. For example, during week four, the slides described scientific observations as being, “used as evidence in scientific explanations” and that “characteristics of scientific observations include accuracy, objectivity, completeness, clarity, [and the] use of labels or scientific vocabulary” (Y2 ESM PowerPoint Week 4). Subsequently, the instructor engaged novice teachers in an activity where they evaluated students’ drawn observations for the characteristics of quality scientific observations, thus providing a further opportunity for the teachers to develop their core content knowledge of science practices.

Lastly, during the Elementary Science Methods course, the novice teachers had further opportunities to develop their knowledge of the science practices when planning, teaching, and reflecting on their science instruction. For example, the Instructional Planning Template used to guide lesson planning prompted the novice teachers to write the science explanation they expected students to develop during the lesson. Following their instruction, the novice teachers were also prompted to reflect on how they felt they “represented the science content and practices [they] were teaching accurately and appropriately” (Y2 ESM Full Scale Science Teaching assignment). These explicit opportunities to develop core content knowledge of science practices differed from the more abstract and varied opportunities evident in the teaching experiences.

The opportunities to learn that supported the teachers’ knowledge of the science practices during their first- and second-years teaching were specific to particular science lessons. For example, Harry mentioned in an interview that observing lessons during student teaching that engaged students in engineering provided opportunities for him to develop his understanding of engineering design (Y3 Harry Interview 2). Similarly, while teaching, Diana continued to develop her understanding of science investigations and the importance of collecting accurate and relevant data. She criticized the use of quantitative data in an investigation about how the body reacts to a stimulus when she said “honestly, I think for just getting [students] started on an investigation just saying, ‘Did your body react? Yes or no’ and write what your body did” (Y3 Diana Interview 1). Compared to the explicit opportunities in the Elementary Science Methods course for developing core content knowledge of science practices, the few opportunities that the teachers mentioned during their teaching experiences were more ambiguous and focused on particular science lessons. This demonstrates the importance of the teacher education program in

providing opportunities that support novice teachers in developing their core content knowledge of science practices.

Opportunities Supporting Teachers' Horizon Content Knowledge

The least supported sub-domain of content knowledge for teaching was horizon content knowledge. Though rarely supported, the few opportunities that did support teachers' horizon content knowledge tended to occur in the Elementary Science Methods course (see Table 4-3). These few opportunities occurred when discussing unit planning and content storylines in two class sessions and in the course readings. For example, one of the course readings stated that

Explicit connections among science ideas across lessons support the development of deep understanding and are central to the notion of a coherent content storyline (ESM Course Reading; Zembal-Saul et al., 2012, p. 48).

Table 4-3. Opportunities to learn in each experience that supported horizon content knowledge (of the total coded opportunities to learn in each experience)

Experiences	Frequency and percentage
Y1: Children as Sensemakers	1/381 (0.3%)
Y1: Teaching with Curriculum Materials	2/296 (0.7%)
Y2: Elementary Science Methods	33/1246 (3%)
Y2: Student Teaching: <i>Claudia</i>	2/25 (8%)
Y2: Student Teaching: <i>Harry</i>	1/26 (4%)
Y2: Student Teaching: <i>Diana</i>	0/34 (0%)
Y3: First Year Teaching: <i>Claudia</i>	3/98 (3%)
Y3: First Year Teaching: <i>Harry</i>	2/114 (2%)
Y3: First Year Teaching: <i>Diana</i>	1/56 (2%)
Y4: Second Year Teaching: <i>Claudia</i>	3/77 (4%)
Y4: Second Year Teaching: <i>Harry</i>	2/89 (2%)
Y4: Second Year Teaching: <i>Diana</i>	2/73 (3%)

Contrary to the theoretical view of horizon content knowledge as an understanding of how concepts and practices develop over time (typically across multiple years) (Ball et al., 2008), the opportunities in the Elementary Science Methods course tended to focus on how concepts relate across a single unit or year of study. Similarly, the minimal opportunities in the teaching experiences that were mentioned in the interviews also tended to focus on the development of ideas across a single unit or year. The minimal opportunities and narrow way of discussing concept development over time provided few chances for novice teachers to develop a deep understanding of how concepts and practices built on what students learned in previous years or would learn in future years.

Opportunities to Learn Pedagogical Content Knowledge

Based on the types of data sources collected, there were more opportunities supporting the teachers' development of their pedagogical content knowledge with most of the opportunities supporting their knowledge of content and teaching. Overall, the majority of the opportunities occurred in the teacher education program with some opportunities also occurring during the teaching experiences (see Figures 4-1 and 4-2). That is not to say that other opportunities did not support their knowledge development, but data on those opportunities were not collected beyond what the teachers discussed during interviews or noted on surveys (e.g., other coursework outside of the teacher education program; professional development experiences).

The following sections articulate the findings for how the opportunities to learn supported each sub-domain within the teachers' pedagogical content knowledge. Due to the prevalence of the opportunities to learn supporting the teachers' knowledge of content and teaching, students, and curriculum, I conducted a second round of coding using emergent codes (Charmaz, 2004) to determine how the opportunities to learn supported aspects of those sub-domains. Doing so

provided insights into how the opportunities supported the teachers' knowledge of teaching, students, and curriculum, as well as identifying gaps where further support might be needed. Findings from that coding are presented in the following sections.

Opportunities Supporting Teachers' Knowledge of Content and Teaching

Knowledge of content and teaching (KCT) was the most supported sub-domain throughout the early years of the teachers' development. This was particularly evident in the Elementary Science Methods course and the Children as Sensemakers course with 66% and 65% of the opportunities, respectively supporting their KCT (see Table 4-4). The opportunities in the Children as Sensemakers course primarily focused on understanding how to elicit students' ideas. For example, when interviewing a student about the day and night cycle, an assignment prompted the novice teachers to ask the student:

If we wanted to show how we have day and night, how could we use these objects? What could be the sun? What could be the earth? How would we shape it to be the earth? Let's put one person on the earth and show how the person would go from day to night (Y1 CaSM Initial Interview Protocol).

Other aspects of the novice teachers' KCT were supported in other experiences in the teacher education program.

Table 4-4. Opportunities to learn in each experience that supported knowledge of content and teaching (of the total coded opportunities to learn in each experience)

Experiences	Frequency and percentage
Y1: Children as Sensemakers	248/381 (65%)
Y1: Teaching with Curriculum Materials	88/296 (30%)
Y2: Elementary Science Methods	819/1246 (66%)
Y2: Student Teaching: <i>Claudia</i>	19/25 (76%)
Y2: Student Teaching: <i>Harry</i>	21/26 (81%)
Y2: Student Teaching: <i>Diana</i>	18/34 (53%)
Y3: First Year Teaching: <i>Claudia</i>	64/98 (65%)
Y3: First Year Teaching: <i>Harry</i>	83/114 (73%)
Y3: First Year Teaching: <i>Diana</i>	48/56 (86%)
Y4: Second Year Teaching: <i>Claudia</i>	27/77 (35%)
Y4: Second Year Teaching: <i>Harry</i>	40/89 (45%)
Y4: Second Year Teaching: <i>Diana</i>	32/73 (44%)

As the primary experience aimed at learning how to teach elementary science, the opportunities in the Elementary Science Methods course supported a variety of aspects of the novice teachers' KCT. Excluding vaguely stated opportunities that did not fall into a particular category, the most frequently provided opportunities supported the novice teachers' knowledge of how to engage students in constructing scientific explanations and arguments, their knowledge of the EEE Framework for organizing science lessons, and their knowledge of how to plan science lessons (see Appendix N for the opportunities to learn supporting KCT). For example, the teacher educator in the Elementary Science Methods course said,

[The EEE Framework] is a very simplified version of an instructional framework that will help you think about how you use science investigations with kids (Y2 ESM Week 1 Video).

As this quote demonstrates, the teacher educator introduced the EEE Framework to support the novice elementary teachers in understanding how to organize science lessons. The EEE

Framework continued to provide a few opportunities for the teachers to develop their understanding of how to organize science lessons during their student teaching experience and their first-year teaching. Building on the opportunities in the teacher education program, the teaching experiences provided further opportunities for the teachers to develop their KCT.

During the teaching experiences, the novice elementary teachers discussed the opportunities to learn as supporting their KCT in different ways. For instance, Claudia explained how her teaching experiences frequently supported her understanding of how to facilitate classroom discussions by learning to ask students, ““Can you explain that in a different way? I respectfully agree or disagree with you. What’s your evidence for that?”” (Y3 Claudia Interview 2). In addition, Diana mentioned opportunities to support her understanding of how to provide “shorter, more to the point way of saying things” for her students (Y4 Diana Interview 1), thereby demonstrating how the opportunities supported her knowledge of how to explain content appropriately.

Overall, the extensive opportunities that supported the novice teachers’ KCT occurred across all experiences both in and beyond the teacher education program. The opportunities primarily supported the teachers’ knowledge of the EEE Framework, lesson planning, and engaging students in constructing explanations and arguments. It also supported the teachers’ knowledge of how to engage students in scientific investigations and science discussions, as well as how to interpret and assess students’ ideas. Though the other aspects of KCT are important for science teaching (e.g., using texts in science; scientific modeling), there were fewer opportunities that supported the novice teachers’ knowledge of those aspects. Further support may be needed to help novices develop their understanding of those aspects of KCT.

Opportunities Supporting Teachers' Knowledge of Content and Students

Opportunities supporting the teachers' knowledge of content and students (KCS) were distributed across the four years with the emphasis on the opportunities in the Children as Sensemakers course (45% of the total opportunities in that course focused on KCS) and the teaching experiences (between 35% and 61% of reported opportunities) (see Table 4-5). Though there were a greater number of opportunities in the Elementary Science Methods course (349 opportunities), supporting this sub-domain was not the focus of that course (only 28% of the opportunities in ESM supported KCS compared with 66% of the opportunities in ESM supporting KCT).

Table 4-5. Opportunities to learn in each experience that supported knowledge of content and students (of the total coded opportunities to learn in each experience)

Experiences	Frequency and percentage
Y1: Children as Sensemakers	173/381 (45%)
Y1: Teaching with Curriculum Materials	14/296 (5%)
Y2: Elementary Science Methods	349/1246 (28%)
Y2: Student Teaching: <i>Claudia</i>	10/25 (40%)
Y2: Student Teaching: <i>Harry</i>	5/26 (19%)
Y2: Student Teaching: <i>Diana</i>	23/34 (68%)
Y3: First Year Teaching: <i>Claudia</i>	41/98 (42%)
Y3: First Year Teaching: <i>Harry</i>	49/114 (43%)
Y3: First Year Teaching: <i>Diana</i>	34/56 (61%)
Y4: Second Year Teaching: <i>Claudia</i>	30/77 (39%)
Y4: Second Year Teaching: <i>Harry</i>	31/89 (35%)
Y4: Second Year Teaching: <i>Diana</i>	33/73 (45%)

The focus of the Children as Sensemakers course was on developing novice teachers' understanding of students as reasonable inquisitors of the world around them, which included students' strengths and challenges related to science concepts. This was evident in the course

syllabus, PowerPoint slides, readings, and course assignments. The syllabus reflects this emphasis by supporting novice teachers' value of students as inquisitors:

An important orientation that successful teachers bring to their work is the presumption that their students are constantly engaged in making sense of the world. Students construct understandings of the world as they interact with others (including their teachers and peers), and as they interact with physical objects (Y1 CaSM Syllabus).

The variety of opportunities in the course included activities during class sessions. For example, during the first class the novice teachers watched a video of a student explaining how she thought she could see an apple in complete darkness. The novice teachers were then prompted to discuss:

What claim does Karen make about whether she will see the apple when there is no light source? How does Karen support her claim? What does this interview with Karen suggest about how people make sense of the world? (Y1 CaSM PowerPoint Week 1).

The novice teachers were also prompted to make sense of how individual students engage in sensemaking during the assignments. The majority of the opportunities supporting the novice teachers' KCS focused on their understanding of students' science ideas and valuing students as scientific sensemakers (see Appendix M).

In contrast, the teaching experiences provided opportunities that supported the teachers' knowledge of individual students' understandings of particular science concepts. This was evident in the interviews when the novice teachers commented about how their interactions with students informed what they knew about the students' science ideas. For example, in a lesson focused on constructing a model tightrope walker, Harry noticed a challenge a student had with models stating,

And so I was trying to bring that out of the student to see if she was able to talk about how the shoes were represented in the model so that she could talk about how they were important. But... it revealed that she had a bit of a lack of understanding of how the model worked and what the model was actually representing, what each piece of the model was representing (Y3 Harry Interview 2).

In some instances, the teachers' opportunities to develop their KCS drove their planning and instruction. Diana mentioned this:

And then I had been talking to the class, like even before I started my unit, and we were talking about scientists. And one kid was like, "Well, I'm not a scientist. I'm not an adult." So then I was like, "Well, I'm going to switch the focus of my unit to being like, this is what scientists can do and you can do all these things. And you're a scientist."

And then it aligned better with the NGSS standards (Y2 Diana Interview 2).

The opportunities in the teaching experiences that supported the novice teachers' KCS primarily supported their understanding of particular students' science ideas.

Overall, the opportunities the novice teachers had to develop their KCS were dispersed across most experiences and varied in how they supported the teachers' knowledge. Most of the opportunities either supported the novice teachers' understanding of students' science ideas or their understanding of students as scientific sensemakers. Few opportunities supported the novice teachers' understanding of how students' cultures, race, genders, nationalities, or identities may influence how students see the world and engage in science. The opportunities that did support this provided more general statements. For example, a PowerPoint slide in the Elementary Science Methods course stated, "Think about students who are often marginalized from science or from school in general" (Y2 ESM PowerPoint Week 4). Though this provided an opportunity

for novice teachers to consider students' cultures, race, genders, nationalities, or identities in who is traditionally encouraged to engage in science or not, it did not provide further suggestions of who is marginalized in science. By looking at how the opportunities provided minimal support for the teachers' understanding of how student diversity influences engagement in science, we see further need of explicit opportunities to help novices know how to engage students in more equitable science teaching.

Opportunities Supporting Teachers' Knowledge of Content and Curriculum

The opportunities supporting the novice elementary teachers' knowledge of content and curriculum (KCC) were mainly emphasized in the Teaching with Curriculum Materials course with some opportunities in the Elementary Science Methods course and the teaching experiences (see Table 4-6). The greatest *frequency* of opportunities occurred in the Elementary Science Methods course due to the extensive data sources. Yet the greatest *emphasis* of the opportunities in a single experience were in the Teaching with Curriculum Materials course, accounting for 72% of its opportunities to learn; this knowledge sub-domain is the conceptual focus of that class.

Table 4-6. Opportunities to learn in each experience that supported knowledge of content and curriculum (of the total coded opportunities to learn in each experience)

Experiences	Frequency and percentage
Y1: Children as Sensemakers	39/381 (10%)
Y1: Teaching with Curriculum Materials	214/296 (72%)
Y2: Elementary Science Methods	334/1246 (27%)
Y2: Student Teaching: <i>Claudia</i>	5/25 (20%)
Y2: Student Teaching: <i>Harry</i>	3/26 (12%)
Y2: Student Teaching: <i>Diana</i>	12/34 (35%)
Y3: First Year Teaching: <i>Claudia</i>	25/98 (26%)
Y3: First Year Teaching: <i>Harry</i>	19/114 (17%)
Y3: First Year Teaching: <i>Diana</i>	14/56 (25%)
Y4: Second Year Teaching: <i>Claudia</i>	27/77 (35%)
Y4: Second Year Teaching: <i>Harry</i>	15/89 (17%)
Y4: Second Year Teaching: <i>Diana</i>	28/73 (38%)

The Teaching with Curriculum Materials course primarily provided opportunities that supported the novice teachers' knowledge of learning goals, assessments, curriculum materials, and standards (see Appendix O). Fewer opportunities supported the teachers' knowledge of how to modify and write learning goals and assessments. The opportunities spanned the syllabus, class PowerPoint slides, and assignments. For example, the class PowerPoint articulated what it means for a learning goal to be well-specified:

1. Well-specified in terms of structure (ABC)
2. Well-specified in terms of thinking (Blooms)
3. Well-specified in terms of type (procedural, content, dispositional, psycho-)
4. Well-specified in terms of size for a lesson (Standard to lesson level)
5. Well-specified in terms of articulation of learning (learning vs. activity or teaching focused) (Y1 TwCM PowerPoint Class 2).

Also, in the assignments the novice teachers were expected to articulate their thinking as to the quality of the learning goals and assessments in lesson plans from curriculum materials. For

example, on assignment three, the novice teachers read a lesson plan from a science unit on weather and were prompted to

Include your thinking about leaving aspects of the original lesson [learning goals] as is, as well as why you made the modifications you did, being sure to make explicit connections to the IPC [Instructional Planning Considerations] (Y1 TwCM Assignment 3).

In comparison, the teaching experiences during the teachers' first two years teaching provided opportunities for the novice teachers to develop their understanding of the science standards and curriculum materials. During interviews, the novice teachers commented about the science standards or about the science curriculum materials they were using (or did not have access to). For example, Claudia commented on the orientation and extent of the district-provided curriculum materials,

I would say our science kits that we get really are helpful for three-fourths of the units that we teach... The one I just taught is already NGSS aligned. The first two we got are not. However, they do include a lot of investigations, but they're structured more in a guided way. And so, I was trying to teach it less that way, but it's a hard shift to make all at once, especially when the kids aren't used to thinking like that. So, the kits are really helpful. They are--there's more in them than we could ever possibly get to (Y4 Claudia Interview 3).

In this example, Claudia's interaction with the curriculum materials during her second-year teaching provided her opportunities to develop her understanding of the quality of curriculum materials.

Overall, the opportunities supporting the novice elementary teachers' development of their KCC spread across the teacher education program and teaching experiences, with particular emphases in the Teaching with Curriculum Materials course. The focus of the opportunities on supporting the novice teachers' knowledge of aspects of curriculum materials (e.g., knowing and evaluating learning goals and assessments) and not as much on how to modify and write learning goals and assessments may lead to less capabilities with engaging in this work of teaching.

Opportunities Supporting Teachers' Knowledge of Connections of Science to Non-Science Disciplines

There were minimal opportunities supporting the novice elementary teachers' knowledge of connections of science to non-science disciplines throughout the teacher education program and only increased slightly when the teachers moved into their first- and second-years teaching (see Table 4-7). The few opportunities that did exist tended to either be general opportunities for considering relationships between disciplines (e.g., graphing in mathematics and graphing for data representation in science) or to focus on the relationships between the Next Generation Science Standards and the Common Core Standards for Mathematics and English Language Arts.

Table 4-7. Opportunities to learn in each experience that supported knowledge of connections of science to non-science disciplines (of the total coded opportunities to learn in each experience)

Experiences	Frequency and percentage
Y1: Children as Sensemakers	2/381 (0.5%)
Y1: Teaching with Curriculum Materials	1/296 (0.3%)
Y2: Elementary Science Methods	40/1246 (3%)
Y2: Student Teaching: <i>Claudia</i>	3/25 (12%)
Y2: Student Teaching: <i>Harry</i>	0/26 (0%)
Y2: Student Teaching: <i>Diana</i>	5/34 (15%)
Y3: First Year Teaching: <i>Claudia</i>	9/98 (9%)
Y3: First Year Teaching: <i>Harry</i>	12/114 (11%)
Y3: First Year Teaching: <i>Diana</i>	9/56 (16%)
Y4: Second Year Teaching: <i>Claudia</i>	6/77 (8%)
Y4: Second Year Teaching: <i>Harry</i>	7/89 (8%)
Y4: Second Year Teaching: <i>Diana</i>	1/73 (1%)

In comparison, during the novice elementary teachers' first two years teaching, they discussed opportunities to make connections primarily between mathematics and English language arts. Only Harry discussed some connections between science and social studies in regard to situating science curricular units in what was being discussed in social studies units.

When opportunities related to connections of science to mathematics, they focused on supporting the teachers' understanding of how to engage students in math discussions, how to use math during data analyses, and how to help students use evidence and reasoning to support their ideas in mathematics. For example, Harry commented on how he was learning to have students engage in discussions that involved students supporting their ideas with evidence in all subjects:

When we have math discussions... we'll do number talks and we'll do discussions about the content that we're learning. And so being able to start with that "I think," "this is why I think that way" and "this is why the evidence that I just gave connects with my thoughts." And so it connects in that way as well... We use that common language across

subjects in order to help them to see that effective arguments can have similar structure across the whole way (Y3 Harry Interview 3).

Similarly, the novice teachers also discussed opportunities to learn how to support students in using evidence to support ideas during English language arts instruction, particularly when knowing how to support students in their writing. For example, when teaching, Claudia developed her understanding of how to help students use common language across disciplines.

And actually using the scientific language with them like “evidence”... And right now we’re doing opinion writing, so it’s like using evidence. And same with “claim.” Today we worked on writing claims for our opinion essays... I try to use that language a lot so that first of all they hear it a lot, they can hear it in different contexts, and then eventually it will become part of their own language. And my goal is that when they’re talking about science they can use words like evidence and claim and observations and investigation and hypothesis and variable and all of those things (Y3 Claudia Interview 2).

In this excerpt, Claudia’s teaching experience allowed her to develop an understanding of how language and practices in science relate to other subjects, including reading and writing in English language arts.

As elementary teachers who teach all subjects, it is not surprising that they had a few more opportunities to develop an understanding of the connections between science and other disciplines, particularly mathematics and English language arts, as they gained more teaching experience.

Opportunities Supporting Teachers’ Knowledge of Applications of Science

The opportunities to support the novice elementary teachers’ understanding of how science concepts and practices relate to social, political, and historical issues and phenomena

beyond the classroom were minimal across all four years with some increases for Harry as he gained more teaching experience (see Table 4-8).

Table 4-8. Opportunities to learn in each experience that supported knowledge of the applications of science (of the total coded opportunities to learn in each experience)

Experiences	Frequency and percentage
Y1: Children as Sensemakers	10/381 (3%)
Y1: Teaching with Curriculum Materials	1/296 (0.3%)
Y2: Elementary Science Methods	37/1246 (3%)
Y2: Student Teaching: <i>Claudia</i>	0/25 (0%)
Y2: Student Teaching: <i>Harry</i>	6/26 (23%)
Y2: Student Teaching: <i>Diana</i>	2/34 (6%)
Y3: First Year Teaching: <i>Claudia</i>	7/98 (7%)
Y3: First Year Teaching: <i>Harry</i>	15/114 (13%)
Y3: First Year Teaching: <i>Diana</i>	4/56 (7%)
Y4: Second Year Teaching: <i>Claudia</i>	5/77 (7%)
Y4: Second Year Teaching: <i>Harry</i>	12/89 (13%)
Y4: Second Year Teaching: <i>Diana</i>	2/73 (3%)

During the teaching experiences, the novice elementary teachers also had minimal opportunities to develop their understanding of how the concepts and practices relate to phenomena beyond a science lesson. In contrast, Harry sought out more opportunities to develop this understanding based on his understanding of his students' experiences and the community. For example, he connected with a local environmental organization, which gave him the opportunity to observe the teaching of an environmental, community-based science unit during his first-year teaching and then to teach that same unit the following year. He also modified an engineering lesson that he observed during a professional development experience in response to his students' fears of failure. When discussing how he thought about science as applicable to students he stated,

A lot of [students] enjoy science but aren't sure how it's useful or unsure how to apply it. So, being able to draw that connection more closely... so, connecting it more broadly with being a member of the community and this is something you do as a member of the community. And all members of the community are scientists, you know?... So, I think that's been really helpful for them to see themselves as scientists (Y4 Harry Interview 3).

Even though understanding how science concepts and practices relate to phenomena beyond the classroom is important for engaging students in science, there were few opportunities for the novice elementary teachers to develop that understanding during the teacher education program and varied opportunities during the teaching experiences.

Summary: Opportunities to Learn CKT-S

There were more opportunities for the novice elementary teachers in the current study to develop their pedagogical content knowledge across both the teacher education program and teaching experiences, compared to the opportunities supporting their subject matter knowledge. It was not surprising that the many opportunities within this teacher education program supported the teachers' pedagogical content knowledge due to the goal of the teacher education program to bridge disciplinary knowledge with knowledge of teaching. Prior to the first-year teaching, the opportunities to develop core content knowledge of science concepts often occurred in coursework outside of the teacher education program (e.g., science content courses, which I did not look at as part of this study). Yet as these novice teachers began interacting with standards, curriculum materials, and students during their planning and instruction, they were confronted with gaps in their core content knowledge of science concepts. Those instances triggered their pursuit of opportunities to expand and deepen their understanding of the science concepts (e.g., Y4 Diana Interview 1; Y4 Harry Interview 3; Y4 Claudia Interview 2). For these

novice elementary teachers, the opportunities that supported their pedagogical content knowledge (KCC, KCS, and KCT) led them to pursue other opportunities to develop aspects of their subject matter knowledge. However, this was only apparent for the teachers' knowledge of the science concepts and not their knowledge of the science practices. The experiences in the Elementary Science Methods course provided the main opportunities to learn about the science practices for these teachers.

Overall, as novice elementary teachers continue to develop their teaching practice, they are confronted with a variety of opportunities in different contexts that may support many aspects of their content knowledge for teaching science. In the current study, no experience supported only one aspect of the teachers' content knowledge for teaching science and often opportunities in one experience supported opportunities in other experiences, demonstrating the need for novice elementary teachers to engage in a variety of experiences to develop all aspects of their knowledge in and for teaching. The next chapter will look at how the novice teachers' CKT-S developed across the four years.

Chapter 5 Novice Elementary Teachers' Development of Their CKT-S

This chapter seeks to answer the research question: *How is novice elementary teachers' content knowledge for teaching science evident in their teaching practice over time?* The following results are based on coding and analyses of video records, lesson plans, reflections, and interviews about the novice elementary teachers' science teaching.

Overall, the novice elementary teachers' SMK was evident throughout their science teaching compared to more varied evidence of their PCK (see Table 5-1). In particular, the novice teachers' understanding of the science concepts and practices was evident throughout their science teaching, but their horizon content knowledge was minimally visible. Within their PCK, the novice teachers' knowledge of content and teaching was most evident and increased as they gained more teaching experience. In comparison, the teachers' knowledge of content and students and knowledge of content and curriculum was more evident in their lesson plans and interviews than during their instruction, yet these sub-domains were still minimally evident throughout their teaching. Also, the teachers' knowledge of the application of science and knowledge of the connections of science to non-science disciplines were minimally evident in their teaching practice.

Table 5-1 represents the number and percentages of coded segments that had evidence of the novice teachers' knowledge of the sub-domains compared to the total number of coded segments for each teaching experience, across all data types. The teaching experiences were the

program year 1 (Y1), program year 2 (Y2), first year teaching (Y3), and second year teaching (Y4).

The next sections outline the analyses for *what* sub-domains of content knowledge for teaching science was evident in the teachers' practices. These sections of this chapter include analyses with examples of the knowledge evident in practice. The final sections outline the analyses of *how* the teachers' core content knowledge of the science practices and knowledge of content and teaching of the science practices were evident in their teaching practice. I discuss those sub-domains related to the science practices in more detail because they are more prominent forms of knowledge evident in the teachers' practice.

Table 5-1. Novice Elementary Teachers' CKT-S Over Time (coded segments / total possible segments)

Teaching Experiences	Subject Matter Knowledge			Pedagogical Content Knowledge			Spans Subject Matter Knowledge and Pedagogical Content Knowledge	
	CCK: SC	CCK: SP	HCK	KCT	KCS	KCC	Applications	Connections to Non-Science
Y1: Claudia	69/127 54%	41/127 32%	8/127 6%	43/127 34%	35/127 28%	56/127 44%	6/127 5%	3/127 2%
Y1: Harry	23/54 43%	16/54 30%	2/54 4%	6/54 11%	2/54 4%	31/54 57%	3/54 6%	1/54 2%
Y1: Diana	69/92 75%	23/92 25%	3/92 3%	16/92 17%	24/92 26%	32/92 35%	4/92 4%	1/92 1%
Y2: Claudia	184/316 58%	201/316 64%	10/316 3%	152/316 48%	79/316 25%	31/316 10%	16/316 5%	13/316 4%
Y2: Harry	140/253 55%	153/253 60%	7/253 3%	103/253 41%	36/253 14%	27/253 11%	14/253 6%	3/253 1%
Y2: Diana	140/250 56%	145/250 58%	11/250 4%	90/250 36%	64/250 26%	38/250 15%	13/250 5%	4/250 2%
Y3: Claudia	355/464 76%	344/464 71%	19/464 6%	295/464 58%	56/464 16%	30/464 8%	27/464 7%	21/464 6%
Y3: Harry	171/284 60%	182/284 64%	1/284 0.4%	132/284 46%	38/284 13%	14/284 5%	16/284 6%	14/284 5%
Y3: Diana	79/113 70%	73/113 65%	0/113 0%	55/113 49%	27/113 24%	7/113 6%	1/113 1%	10/113 9%
Y4: Claudia	242/296 78%	166/296 54%	11/296 5%	118/296 44%	46/296 11%	25/296 11%	22/296 7%	6/296 3%
Y4: Harry	143/233 61%	111/233 48%	5/233 2%	85/233 36%	25/233 11%	18/233 8%	37/233 16%	7/233 3%
Y4: Diana	181/309 59%	154/309 50%	8/309 3%	95/309 31%	43/309 14%	31/309 10%	0/309 0%	5/309 2%

Core Content Knowledge: Science Concepts

The novice teachers' core content knowledge of the science concepts was evident in all of their science lessons across all four years (see Figure 5-1). Almost half or more of the segments had evidence of the teachers drawing on their knowledge of the science concepts. For example, during a lesson on the local watershed and how water moves through the watershed Harry said,

A watershed is an area of land that water flows on or through to get to a river, creek, lake, bay, or ocean (Y4 Harry Video 1.1).

Between 42.6% and 81.8% of segments included this sub-domain, across all of the data. Even as the teachers moved into their challenging first two years of teaching, they continued to draw on their knowledge of the science concepts. Also, the novice elementary teachers' understandings of the science concepts served as foundations for science investigations, because that was the foci of the videorecorded lessons.

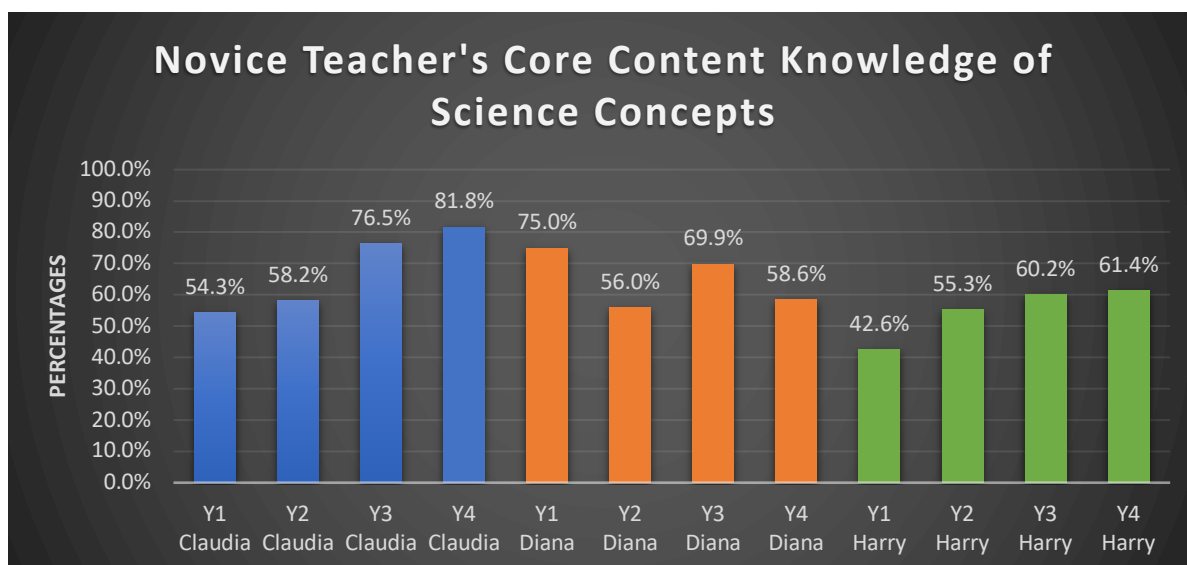


Figure 5-1. Evidence of Novice Teachers' Core Content Knowledge of the Science Concepts Across Time

Core Content Knowledge: Science Practices

The novice teachers' core content knowledge of the science practices was evident in almost all of the lessons (see Figure 5-2) during the second year in the teacher education program and the first two years of teaching. The teachers' knowledge of the science practices increased in their second year in the teacher education program, which was not surprising because that was when they took the Elementary Science Methods course and became introduced to the science practices (see Chapter 4). Specifically, the evidence of their knowledge of the science practices ranged from 25-32.3% of segments in their first year in the teacher education program to 47.4-74.1% in the latter three years.

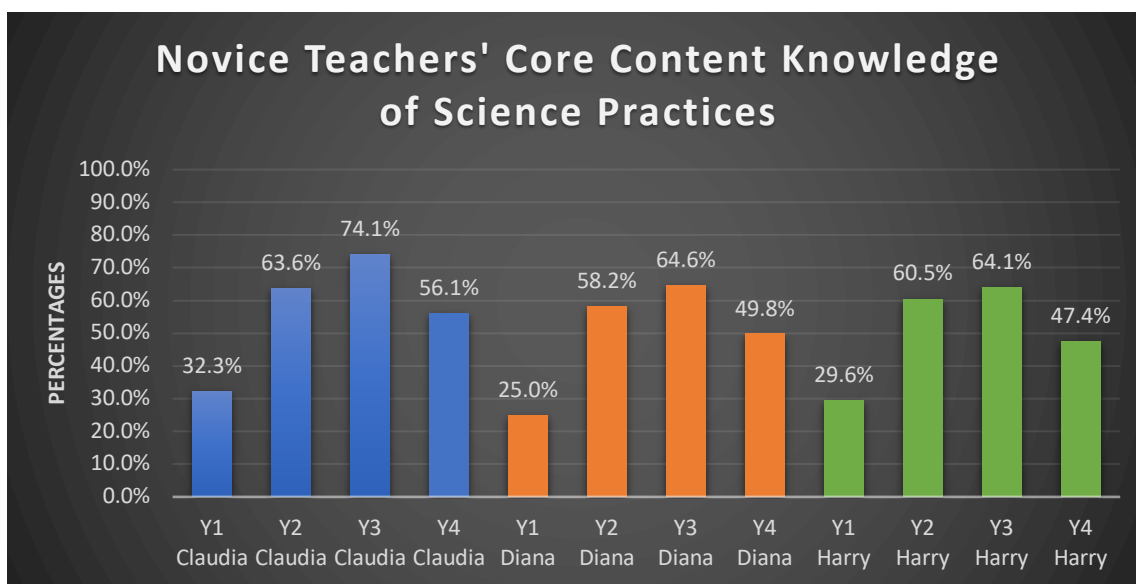


Figure 5-2. Evidence of Novice Teachers' Core Content Knowledge of the Science Practices Across Time

During many lessons, the teachers drew on their knowledge of different science practices. This included their understanding of scientific questions, investigations, predictions, observations, explanations and arguments, modeling, and data analyses. For example, knowing what scientific investigations are involves knowing about variables and controls. Claudia drew

on this knowledge during instruction in a lesson about pendulum motion during her first year of teaching when she said,

What were some of those things that we kept the same, we controlled some of those variables? (Y3 Claudia Fall Video 1.1).

In this example, Claudia drew on her knowledge of controls when discussing the controls in the investigations about what causes changes in a pendulum's motion. Though the novice teachers' knowledge of the science practices was evident in most lessons, how they drew on their knowledge of the different science practices varied based on the lessons they taught. This is discussed in further detail in the final sections of this chapter.

Horizon Content Knowledge

The teachers' horizon content knowledge was rarely evident in their instruction across the four years, ranging from no evidence (Year 3 Diana) to 6.3% of instances (Year 1 Claudia). In the few instances when the teachers did make statements drawing on their horizon content knowledge, they tended to represent their understanding of how science concepts or practices related to previous or upcoming science lessons in the same unit. For example, Diana mentioned, "remember on Friday we were learning about our sense of taste..." (Y2 Diana Video 2.1). Even in the interviews when asked about their horizon content knowledge, the teachers mentioned that they "don't feel very prepared" (Y4 Harry Interview 3) regarding their understanding of how the science concepts and practices they teach build on learning in previous years or inform those taught in later years.

Knowledge of Content and Teaching

The novice elementary teachers' knowledge of content and teaching, a dimension of PCK that reflects an understanding of how to engage students in the science practices, varied across

the four years (see Figure 5-3). For example, the teachers' knowledge of content and teaching about scientific investigations involved knowing how to model an investigation for students without giving away the results. Harry demonstrated this understanding during a lesson on circuits and electric current in his first-year teaching when he said,

You are going to light up a bulb using only these materials: a battery, wire, a battery holder, and a light bulb... When I give you this paper, you are going to begin to think about how to put those materials together in order to transfer the energy and light the bulb (Y3 Harry Energy Video 1.1).

In this example, Harry's comment represented his understanding that students need to be guided in how to conduct the investigation without being told what will happen in the investigation.

Harry was careful not to show the students what to do when creating a circuit, which would give away the results of the investigation.

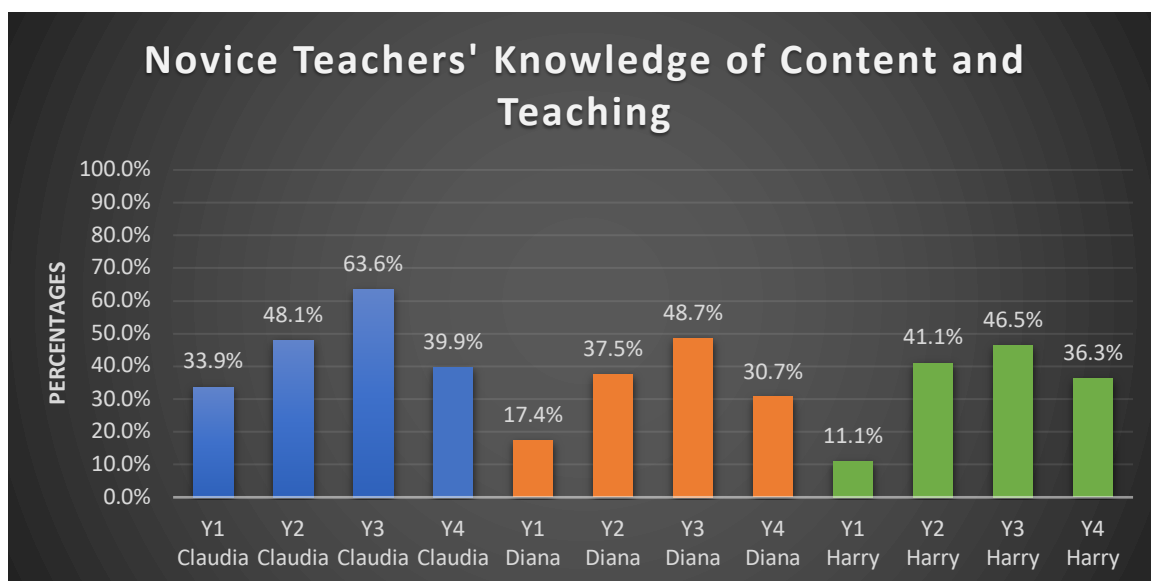


Figure 5-3. Evidence of Novice Teachers' Knowledge of Content and Teaching Across Time

The teachers' knowledge of content and teaching was less evident in their first year in the teacher education program and more evident as they gained more teaching experience in their second year in the program and their first-year teaching. For example, it ranged from 33.9% of segments in Claudia's first year in the teacher education program to 63.6% in her first-year teaching. The teachers' knowledge of content and teaching was less evident in their second year of teaching. Further work is needed to investigate why it might be that the evidence of teachers' knowledge of content and teaching decreased as they moved into their second year of teaching.

Knowledge of Content and Students

There were fewer instances when the teachers drew on their knowledge of content and students (see Figure 5-4) compared to their core content knowledge or knowledge of content and teaching. Evidence of this knowledge ranged from 3.7% to 27.6% of the coded segments. During the first year of the teacher education program, the teachers took a course focused on children as scientific sensemakers, which was likely why the evidence of Claudia and Diana's knowledge of content and students was highest during that time. There were fewer data sources for Harry during the first year in the program, which is likely why there is less evidence of his knowledge at that time. In general, though not as evident, the teachers were consistent in the extent to which they drew on their knowledge of content and students in their teaching practice. Among other elements, this knowledge includes the teachers' understanding of students' ideas or challenges related to science concepts and practices. The few instances in the teachers' instruction where this knowledge was visible tended to be about students' challenges engaging in the science concepts or practices. For example, during her second-year teaching Claudia said,

We are going to come back to some of the questions you all have asked...what does it actually mean to be living? Is water a living thing? And...is the sun living? (Y4 Claudia Nutrient Systems Video 2.1).

This demonstrated her understanding that students struggled with the concept of what constitutes a living thing, which guided a lesson where the students used different texts to create a class definition of what it means to be living (see the section below on Obtaining, Communicating, and Evaluating for more about this lesson).

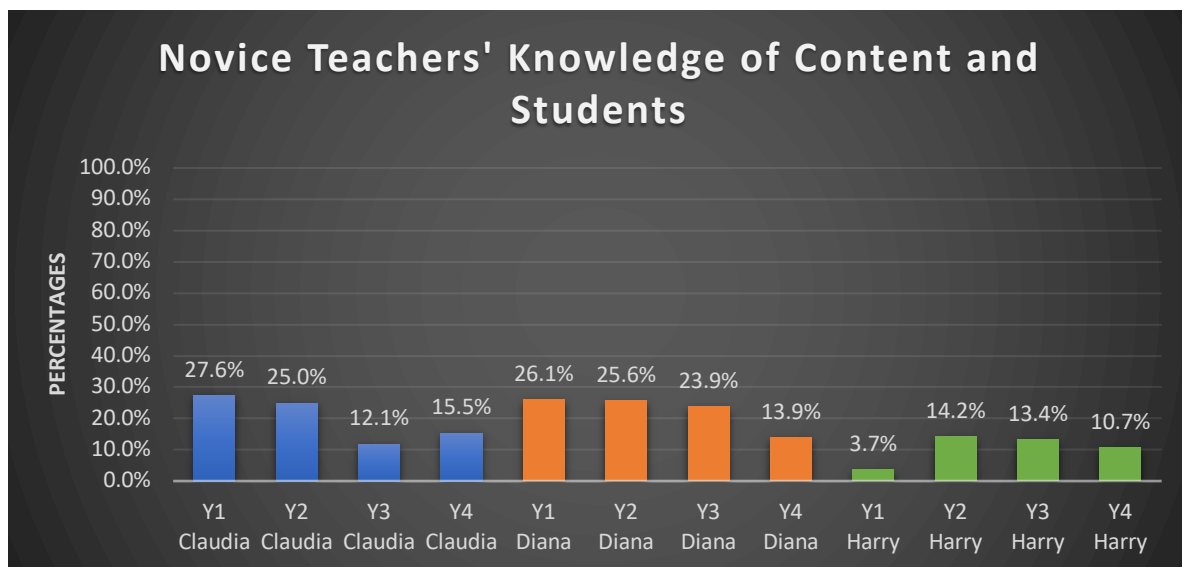


Figure 5-4. Evidence of Novice Teachers' Knowledge of Content and Students Across Time

Knowledge of content and students was more evident in the teachers' lesson planning and reflections on their teaching than in their enacted instruction. For example, almost half of Claudia's lesson plans and interviews demonstrated her knowledge of content and students. In an interview during her first-year teaching, she said,

I think one of the biggest challenges and misconceptions is that those arrows [on a food chain diagram]...are meant to represent the energy transfer. And often times, kids will draw the arrows the opposite way (Y3 Claudia Interview 3).

This demonstrated her understanding of students' challenges with representing energy movement in a food chain diagram. This knowledge was a guide for what she taught and how she engaged her students during instruction though was not often stated during instruction. This meant that the teachers' knowledge of content and students was likely more of an implicit understanding informing teaching practice yet not always evident to the students through talk during instruction.

Knowledge of Content and Curriculum

Similar to the novice teachers' knowledge of content and students, their knowledge of content and curriculum was minimally evident in their second year in the program and first two years of teaching but was much more evident in their first year in the program (see Figure 5-5). During the first year in the program, the teachers took a course called Teaching with Curriculum Materials, which was likely why their knowledge of content and curriculum was more evident at that time. The teachers' knowledge of content and curriculum often reflected their understanding of the science curriculum and standards with some evidence of their understanding of assessments. For example, Diana said,

When I was looking at the standards, there would be just kind of going into what they actually want the kids to know to answer that standard. Like, what's the information necessary to answer that or to meet that kind of expectation (Y4 Diana Interview 1).

This demonstrated her understanding that science assessments can be used as evidence of students achieving goals stated in standards documents. Similar to the teachers' knowledge of

content and students, the teachers' knowledge of content and curriculum was more evident in their lesson planning and reflections on their teaching compared with their instruction. For example, almost a quarter of Claudia's lesson plans, interviews, and reflections demonstrated her knowledge of content and curriculum, specifically, her understanding of the science curriculum materials and the standards.

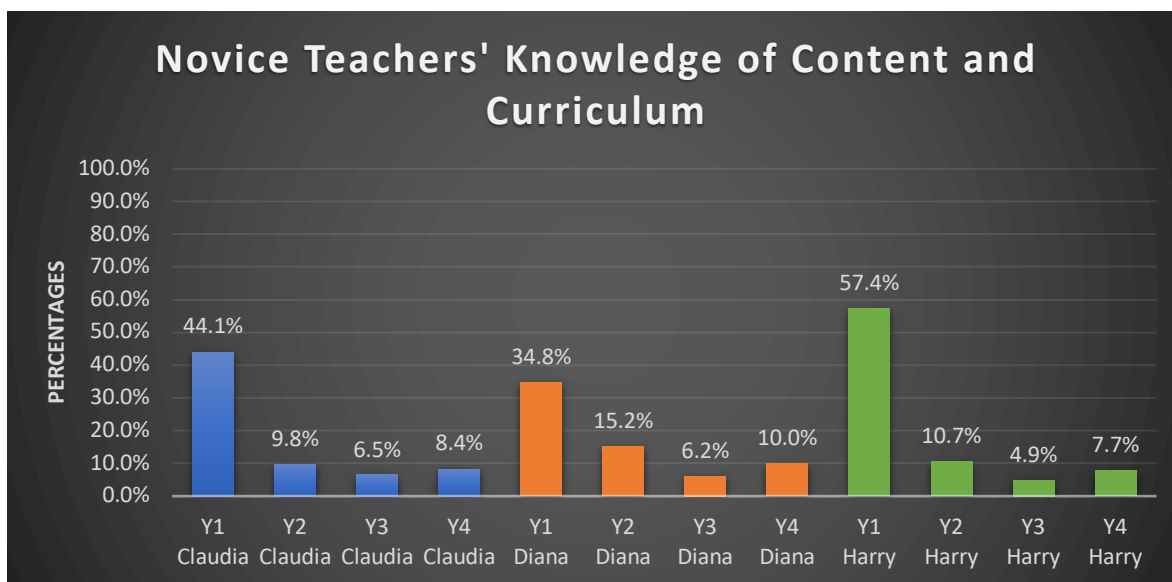


Figure 5-5. Evidence of Novice Teachers' Knowledge of Content and Curriculum Across Time

Knowledge of the Application of Science

The novice teachers' knowledge of the application of science was minimally evident across the four years (see Figure 5-6) and more likely to be evident when prompted by the curriculum or when a student brought up an idea that required the teacher to apply an understanding of the concepts or practices to phenomena beyond the lesson. For example, Harry taught a science unit during his second-year teaching about the local watershed and surrounding environment near the school which led to discussions of the connections between the concepts

taught in the classroom and the local community. During an initial lesson about environments, Harry mentioned the school garden and applied the concept of an environment to this familiar place. He said,

If the garden is the example of an environment... the types of weather we have in an environment affects the types of food we have in that environment, which affects what lives there (Y4 Harry Video 1.1).

Though not a complete description of an environment, he applied the concept of an environment to familiar phenomena beyond the lesson's focus on wetlands in order to support students' understanding of the broader concept. The range of the evidence of the teachers' knowledge of the application of science was from 0% to 15.9% of segments. Though it is important for teachers to understand how the science concepts and practices taught in the classroom relate to phenomena beyond of the classroom (Kloser, 2014), there were few instances where this knowledge was evident in these novice teachers' instruction.

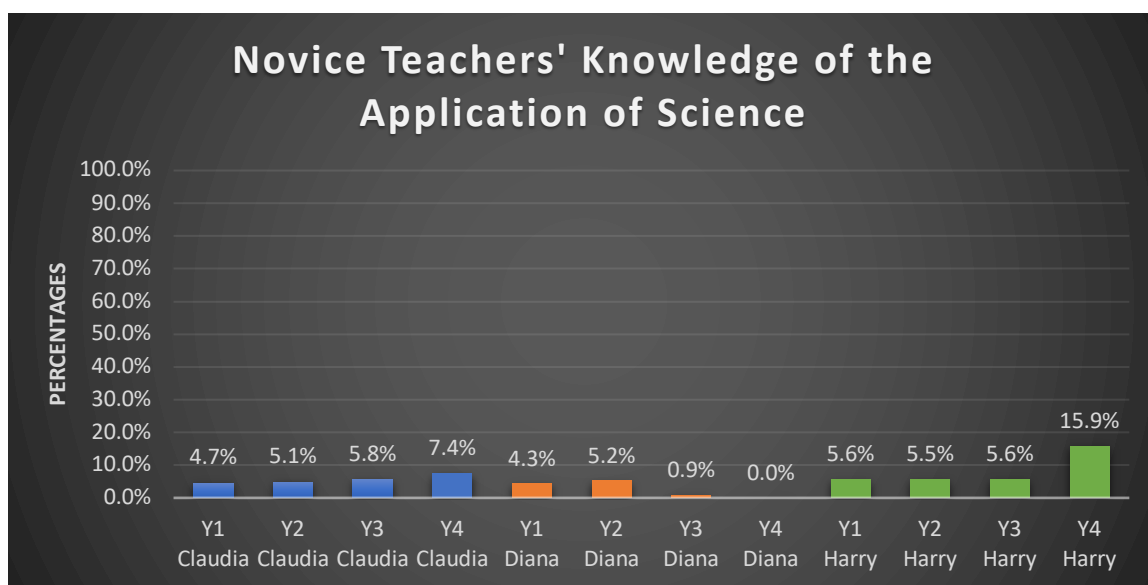


Figure 5-6. Evidence of Novice Teachers' Knowledge of the Application of Science Across Time

Knowledge of the Connection of Science to Non-Science Disciplines

Similar to the teachers' knowledge of the application of science, their knowledge of the connections of science to non-science disciplines was minimally evident across the four years (see Figure 5-7). Their knowledge of the connections of science to non-science disciplines was slightly more evident during their first-year of teaching but was less evident in their second-year of teaching. An example of Diana's knowledge of the connection of science to non-science disciplines was evident in her first-year of teaching when she taught her students how to graph in order to analyze data. She said, "we're actually going to be learning this in math this week..." (Y3 Diana Video 1.1). She drew on her understanding of the mathematics curriculum (a mathematical form of knowledge of content and curriculum) and connected this to the need to analyze quantitative science data (core content knowledge for teaching about analyzing data). In the few instances when the teachers drew on this knowledge, they tended to make comments connecting to a topic taught in another subject and not to *how* the topic relates to the science concepts and practices in the lesson. Overall, there were few instances when the teachers' knowledge of the connection of science to non-science disciplines was evident in their teaching practice.

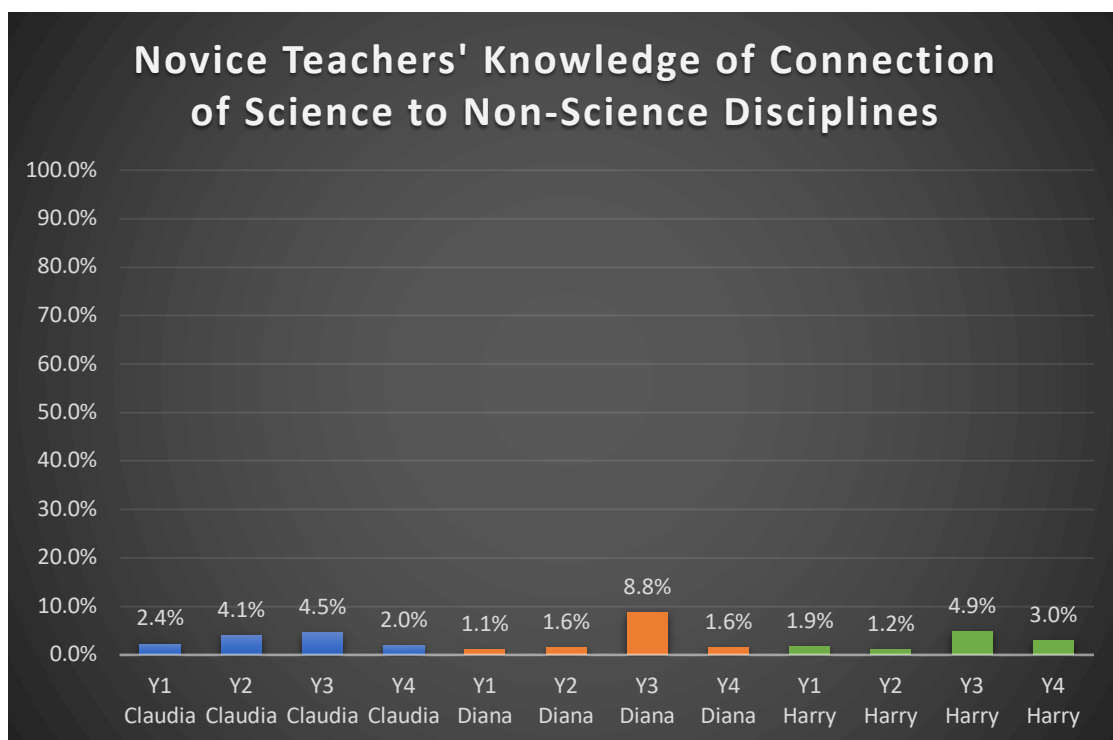


Figure 5-7. Evidence of Novice Teachers' Knowledge of the Connection of Science to Non-Science Disciplines Across Time

Summary: Evidence of Teachers' Knowledge of All Sub-Domains

Overall, some sub-domains of these novice elementary teachers' SMK and PCK were more evident than other sub-domains during their instruction. Specifically, the novice teachers' core content knowledge of the science concepts and practices and their knowledge of content and teaching were more evident in their instruction. There was a drop, however, in the evidence of the teachers' knowledge of those sub-domains during year 4 compared with year 3. This drop from year 3 to year 4 may be due to the difference in data sources in year 4. In year 4, the data was from one full science unit. In contrast, in year 3 the data was from investigation-based science lessons spread across the academic year. Though having data from one unit allows for evidence of teachers' knowledge from more varied lessons, the lessons are not necessarily all

investigation-based (e.g., units often include lessons where students read science texts). Another possibility as to why there was less evidence of these teachers' knowledge in year 4 compared with year 3 may be that these teachers worked hard during their first year teaching (year 3) to teach in ways that reflected their learning how to teach science during year 2. In their second year teaching (year 4), however, these teachers may have either been less attentive to teaching in ways that reflected their instruction in the Elementary Science Methods course or they may have been occupied with other classroom responsibilities. Overall, it is unclear as to why there was a drop in the evidence of knowledge during year 4 compared with year 3.

Across the four years, the novice teachers in the current study also demonstrated minimal knowledge of the other sub-domains. In particular, their knowledge of content and students and knowledge of content and curriculum were minimally evident in their instruction with more evidence in their lesson planning and reflections on their science teaching. Lastly, the teachers' horizon content knowledge, knowledge of the applications of science, and their knowledge of the connection of science to non-science disciplines was minimally evident throughout their teaching practice.

Quality of the Teachers' Knowledge of the Science Practices

The previous sections focused on the amount of each knowledge sub-domain that was visible in the teachers' practice. This section outlines the *quality* of the teachers' core content knowledge (CCK) and their knowledge of content and teaching (KCT) of the science practices across the four years. I focus on those knowledge sub-domains because of the greater evidence of those sub-domains compared to other sub-domains. Also, I focus on the science practices because of the minimal research on teachers' knowledge of the science practices (e.g., Davis et al., 2006) compared to their knowledge of the science concepts (e.g., Abell, 2007). To study the

quality of their knowledge I developed rubrics that outline the dimensions of each science practice that the teachers should know (e.g., National Research Council, 2012; NGSS Lead States, 2013) and dimensions of teachers' knowledge of how to engage students in each science practice (e.g., Rivet & Ingber, 2017). The teachers' videos, lesson plans, reflections, and interviews were scored as does not meet (1), approaches (2), meets (3) or exceeds expectations (4) for each dimension of each science practice. These scores were used to determine the means and ranges of the teachers' understanding of each dimension of the science practices. In doing so, I found variation in how the teachers made sense of the science practices and ways to engage students in them.

Overall, I found that the teachers' KCT for each science practice was, in general, stronger than their CCK of the science practices. In other words, they had a greater understanding of how to engage students in the science practices compared to understanding the dimensions of each science practice. There were particular science practices that they demonstrated a stronger understanding of than others. Specifically, the teachers demonstrated the strongest understanding of constructing scientific explanations and arguments, which was not surprising since the Elementary Science Methods course focused extensively on these science practices. In contrast, the teachers' core content knowledge was the lowest for science investigations, though they still demonstrated moderate to strong understanding of how to engage students in science investigations (i.e., their KCT for that practice). The teachers varied in how they made sense of the different science practices.

The following sections outline how the teachers made sense of each science practice with supporting quotes from the teachers' planning, instruction, and reflection about the science

practices. The final section characterizes relationships across the dimensions of all of the science practices.

Teachers' Knowledge of the Science Practices

In this section I discuss the teachers' knowledge of asking questions, investigations, predictions, observations, analyzing and interpreting data, explanations and arguments, modeling, and obtaining, evaluating, and communicating information. The only science practice not discussed in this dissertation is mathematical and computational thinking due to its limited evidence in elementary classrooms in general (Plumley, 2019), and also in the classrooms of these three teachers.

Within each section I include a table with the teachers' overall mean scores for CCK and KCT for each science practice. I also include the range of scores (in parentheses) received across their teaching experiences throughout the four years. The "n" represents the total number of segments with evidence of the teachers' knowledge of any science practice. Due to the nature of the coding, I was not able to determine the total number of segments with evidence of the teachers' knowledge for each science practice.

Scientific Investigations. The novice elementary teachers demonstrated mean scores ranging from 1.53 to 2.73 for understanding scientific investigations, yet they still had a strong understanding of how to engage students in scientific investigations (KCT) (see Table 5-2). The dimensions of CCK of scientific investigations included knowing that investigations (a) include variables and controls and (b) involve systematically collecting data (National Research Council, 2012; NGSS Lead States, 2013). Claudia demonstrated the strongest understanding of the dimensions of scientific investigations, yet her understanding still fell within "approaches

expectations.” For example, during Claudia’s first year teaching she discussed controls and variables stating,

The independent variable is the one we are changing and that is the length of the pendulum... If we are changing the link, what are all the other things that we need to control and keep the same? (Y3 Claudia Video Fall 1.3).

In comparison, Harry and Diana’s mean scores both were below a 2.0 because they rarely talked about the variables and controls in the investigations, when applicable, and they did not typically discuss the systematic nature of science investigations.

Table 5-2. Novice elementary teachers’ content knowledge for teaching (CKT) about scientific investigations (Claudia: n=752; Diana: n=395; Harry: n=462)

	CCK	KCT
	Mean score	Mean score
	(range)	(range)
Claudia	2.73 (1-4)	3.65 (1-4)
Diana	1.69 (1-4)	3.52 (1-4)
Harry	1.53 (1-3)	3.80 (2-4)

The teachers’ KCT mean scores ranged from 3.52 to 3.80 – much higher than their CCK scores. Harry, in particular, had a low CCK mean score, yet scored quite high for his understanding of how to engage students in scientific investigations (KCT). The dimensions of KCT for scientific investigations were knowing (a) how to model an investigation without giving away the results, (b) how to circulate and ask sensemaking questions related to the investigation, and (c) that students should be conducting the investigation (Crawford, 2000; Harris et al., 2012; Kademian, 2017; Metz, 2008). For example, during his teaching in the Elementary Science Methods course, Harry wrote questions in his lesson plan to ask students while circulating,

Backpocket questions: What do you notice about the temperature of the hot water? Cold water? How do the temperatures compare? How are the temperatures changing over time? (Y2 Harry Lesson Plan 1).

This demonstrates his understanding that when engaging students in conducting scientific investigations, it is important to circulate to each group and ask scientific sensemaking questions.

Overall, though the teachers did not have a strong understanding of what scientific investigations are, they still understood how to engage students in the science practice. This indicates the potential that their pedagogical knowledge may have mediated their limited CCK to increase their KCT for scientific investigations.

Scientific Predictions. The novice elementary teachers demonstrated higher CCK of scientific predictions than scientific investigations, though their KCT was not as strong as KCT of scientific investigations (see Table 5-3). The teachers' CCK mean scores for scientific predictions ranged from 2.00 to 2.86, which was within an "approaches expectations" level. The dimensions for CCK of scientific predictions were (a) knowing that scientific predictions should include a justification and (b) that they should be revisited based on new data or information (Duschl & Osborne, 2002; National Research Council, 2012; NGSS Lead States, 2013). For example, when planning for her teaching during the Elementary Science Methods course, Diana wrote,

Have the students make their predictions. Remind them that scientists say why they think something will happen and ask them why they think the water level will go up/down/stay the same (Y2 Diana Lesson Plan 1).

This demonstrates Diana's understanding that predictions should include a justification even though she did not support her students in providing one (Y2 Diana Video 1).

Table 5-3. Novice elementary teachers' CKT about scientific predictions (Claudia: n=752; Diana: n=395; Harry: n=462)

	CCK	KCT
	Mean score	Mean score
	(range)	(range)
Claudia	2.65 (1-4)	3.03 (1-4)
Diana	2.86 (1-4)	3.07 (1-4)
Harry	2.00 (1-4)	3.11 (1-4)

In comparison, the teachers' KCT mean scores about predictions were just above 3, which "meets expectations" for this understanding. The dimensions for KCT about predictions were (a) knowing to prompt students for a justification with a prediction, (b) knowing to prompt students to revisit their predictions, (c) knowing that predictions should be recorded, and (d) knowing that students should make their own predictions (Arias et al., 2017; Lee & Butler, 2003). For example, while teaching in his second year, Harry asked students to share their predictions and he recorded the predictions on the board. He prompted a student further by asking, "What makes you think that?" (Y4 Harry Video 1.3). This interaction demonstrated his understanding that teachers need to prompt students for justifications with their predictions and that predictions should be recorded.

Scientific Observations. The novice elementary teachers' mean scores for CCK of scientific observations ranged from 2.25 to 2.60, which fell within the "approaches expectations" level (see Table 5-4). The dimensions of CCK for scientific observations included (a) knowing that high quality scientific observations are accurate, complete, clear, objective, and labeled, and (b) knowing that scientific observations are used as evidence for explanations and arguments (Arias & Davis, April 2016; Duschl & Bybee, 2014; Eberbach & Crowley, 2009; National

Research Council, 2012; NGSS Lead States, 2013; Zembal-Saul, 2009; Zembal-Saul et al., 2012). Diana demonstrated this understanding when reflecting on her teaching during her first year by stating,

The way we discussed observations was what you see...and bringing in types of scientific drawings, like labels, making it as close to what you observe as possible (Y3 Diana Interview 2).

This demonstrates her understanding that scientific observations are accurate and include labels, though in this lesson she did not demonstrate an understanding that scientific observations should also be complete, clear, and objective.

Table 5-4. Novice elementary teachers' CKT about scientific observations (Claudia: n=752; Diana: n=395; Harry: n=462)

	CCK	KCT
	Mean score	Mean score
	(range)	(range)
Claudia	2.60 (1-4)	3.05 (2-4)
Diana	2.31 (1-4)	3.03 (2-4)
Harry	2.25 (1-4)	2.96 (1-4)

The teachers' KCT was relatively low compared to other science practices with mean scores ranging from 2.96 to 3.05. The dimensions of KCT for scientific observations included knowing (a) how to model how to make high quality scientific observations, (b) that students need tools for making observations, (c) that students should share their observations with others, and (d) that students should be making their own scientific observations (Arias & Davis, April 2016; Duschl & Bybee, 2014; Eberbach & Crowley, 2009). For example, Claudia modeled how to make observations of butterflies during her second-year teaching by observing butterflies with

student groups and then making a model observation. Overall, the teachers' relatively lower understanding of scientific observations and how to engage students in this practice demonstrates the need for further support for knowing how to engage students in this work, particularly as the teachers move into their first few years teaching.

Analyzing and Interpreting Data. Compared to their knowledge of the other science practices, except for science investigations, the novice elementary teachers demonstrated low CCK related to analyzing and interpreting data with mean scores ranging from 1.94 to 2.28 (see Table 5-5). The dimensions of this science practice include (a) knowing that analyzing and interpreting data involves giving meaning to data, (b) knowing that representations are used to analyze and interpret data, (c) knowing that errors can occur when collecting data, and (d) knowing that interpreting data involves gathering consensus about the meaning of multiple data sets (National Research Council, 2012; NGSS Lead States, 2013, Appendix F; Rivet & Ingber, 2017). For example, Claudia said when reflecting on her teaching in her first year,

I think that was important to have that conversation [about errors in data] because the visual graph allows you to really easily see where things look out of place, but also see that pattern... organizing it in that way and being able to look at the relationships right next to each other and seeing the patterns (Y3 Claudia Interview 1).

This demonstrates her understanding about the importance of using a representation to make sense of data and the need to identify potential errors in data.

Table 5-5. Novice elementary teachers' CKT for analyzing and interpreting data (Claudia: n=752; Diana: n=395; Harry: n=462)

	CCK Mean score (range)	KCT Mean score (range)
Claudia	2.28 (1-4)	3.46 (1-4)
Diana	1.94 (1-4)	3.50 (1-4)
Harry	2.17 (1-4)	3.07 (1-4)

The novice elementary teachers' KCT for analyzing and interpreting data was relatively high compared with their low CCK. Their KCT mean scores for analyzing and interpreting data ranged from 3.07 to 3.50. The dimensions for KCT of analyzing and interpreting data include (a) knowing to prompt students for evidence with their ideas, (b) knowing to prompt students to identify patterns in the data, (c) knowing how to use representations to support students in analyzing and interpreting data, and (d) knowing that students should analyze and interpret the data themselves (Rivet & Ingber, 2017). Diana demonstrated this understanding during her teaching in the Elementary Science Methods course when she provided a representation of the data and prompted her students for patterns in the data by saying, "What changed, what made the water go up higher and higher?" (Y2 Diana Video 1). This demonstrated her understanding of how to use a representation to analyze and interpret data and to prompt students for patterns in the data.

Overall, the teachers' higher KCT scores for analyzing and interpreting data, similar to scientific investigations, may indicate that the teachers' pedagogical knowledge mediated their limited subject matter knowledge (for which CCK is a sub-domain) leading to an increase in their pedagogical content knowledge (for which KCT is a sub-domain). It also highlights that even if teachers struggle to understand the dimensions of a science practice, they may still

reasonably understand how to engage students in the science practice as long as it does not involve articulating the details of the practice itself. For example, the teachers struggled to understand that analyzing and interpreting data involves giving meaning to data, yet they knew to prompt students to identify patterns in the data. In this way the teachers could reasonably engage students in the science practice even though they struggled to understand the nuances of the science practice itself.

Scientific Explanations and Arguments. The novice elementary teachers' CCK of constructing scientific explanations and arguments was the highest for all of the science practices. Their mean scores ranged from 2.79 to 3.34 (see Table 5-6), which was the higher end of “approaches expectations” to “meets expectations.” The higher mean scores were not surprising since the Elementary Science Methods course focused extensively on these science practices through the use of the claim-evidence-reasoning heuristic. For this reason, the dimensions of CCK for these science practices include (a) knowing that scientific explanations and arguments include a claim supported by evidence and reasoning, (b) knowing that a claim answers an investigation question, (c) knowing that evidence is gathered from data and is used to support the claim, and (d) knowing that reasoning connects the evidence to the claim and includes a scientific principle (McNeill et al., 2006; National Research Council, 2012; NGSS Lead States, 2013, Appendix F; Zembal-Saul et al., 2012).¹² Claudia demonstrated this understanding when planning for a lesson with sixth-graders about energy transfer while in the Elementary Science Methods course. She wrote in her lesson plan, “Reasoning is the justification

¹² The novice elementary teachers were taught about scientific explanations and arguments through the use of a heuristic for to develop claims supported by evidence and reasoning (Zembal-Saul et al., 2012). For this reason, the dimensions for understanding scientific explanations and arguments focused on the parts of the heuristic.

that helps connect the claim and evidence. Draws upon scientific principles” (Y2 Claudia Lesson Plan 1).

Table 5-6. Novice elementary teachers’ CKT about scientific explanations and arguments (Claudia: n=752; Diana: n=395; Harry: n=462)

	CCK	KCT
	Mean score	Mean score
	(range)	(range)
Claudia	3.34 (1-4)	3.64 (1-4)
Diana	2.79 (1-4)	3.29 (1-4)
Harry	3.24 (1-4)	3.61 (2-4)

The novice elementary teachers’ KCT about scientific explanations and arguments was also fairly high with their mean scores ranging from 3.29 to 3.64, which is “meets expectations.” The dimensions of their KCT for scientific explanations and arguments included (a) knowing how to provide supports for students’ construction of explanations and arguments, (b) knowing that students should create the claim, (c) knowing that students should identify the evidence, and (d) knowing that students should construct the reasoning (Berland & McNeill, 2011; McNeill & Krajcik, 2008; Zembal-Saul et al., 2012). Harry drew on this understanding in his second-year teaching when he provided sentence starters for his students during a lesson on estuaries. He said,

Your claim is going to start with a sentence stem, ‘I think that ____’... For our evidence we are going to say, ‘In our model, I observed (and observed is a scientific word for ‘saw’) that ____’... Now we have to say how does what we saw in our model connect with what we think... You’re going to start by saying, ‘This evidence proves that my claim is correct because ____’ (Y4 Harry Video 1.5).

This demonstrates his understanding of how to provide supports for students when constructing an argument using the claim, evidence, and reasoning heuristic. Overall, the teachers' understanding of explanations and arguments and how to engage students in these science practices was fairly high throughout their teaching experiences.

Scientific Modeling. The novice elementary teachers demonstrated low to moderate CCK of scientific modeling and their KCT was the lowest of all of the science practices (see Table 5-7). Their mean scores for CCK for scientific modeling ranged from 1.78 to 2.96. This was not surprising since the Elementary Science Methods course did not focus on scientific modeling. The dimensions of scientific modeling included (a) knowing that models represent the natural world and are used to test hypotheses, (b) knowing that models foreground and background different aspects of the natural world, and (c) knowing that models should be evaluated and revised based on new data (National Research Council, 2012; NGSS Lead States, 2013; Schwarz et al., 2009). Harry demonstrated this understanding when he stated,

When we create our bay in the box today, we are going to be replicating that with our model... so we want our saltwater to be in the ocean and our freshwater to be up here in the... river and see where it goes (Y4 Harry Video 1.3).

In stating this, he demonstrated that he understood that models represent the natural world. In this lesson, he did not demonstrate an understanding that models should test hypotheses.

Table 5-7. Novice elementary teachers' CKT about scientific modeling (Claudia: n=752; Diana: n=395; Harry: n=462)

	CCK	KCT
	Mean score	Mean score
	(range)	(range)
Claudia	2.26 (1-4)	2.95 (1-4)
Diana	1.78 (1-3)	2.80 (1-4)
Harry	2.96 (1-4)	3.41 (1-4)

Even though the teachers had some understanding about scientific modeling, they were not always aware of this understanding. For example, though Harry discussed modeling in his instruction during his first-year teaching about a tightrope walker, he began the lesson by referring to this as “engineering” and later in the lesson shifted to using the language of “modeling.” Similarly, the teachers at times discussed “conducting investigations” during interviews when the work they were doing in their instruction was actually scientific modeling. There were inconsistencies in the teachers’ own sensemaking about scientific modeling.

The teachers had less KCT for scientific modeling than the other science practices. Their mean scores ranged from 2.80 to 3.41, which was from “approaches expectations” to “meets expectations.” The dimensions for teachers’ KCT related to scientific modeling includes (a) knowing how to support students in understanding the aspects of the natural world that models do and do not represent, (b) knowing that students should construct scientific models themselves, (c) knowing how to support students in evaluating and revising scientific models based on data, and (d) knowing how to support students in using models to explain phenomena (Passmore et al., 2017; Schwarz et al., 2009; Windschitl et al., 2008). Harry demonstrated this understanding in the same unit as above about modeling the estuary between a river and the ocean by stating

We are going to be using the same types of water yesterday (saltwater and freshwater).

The blue water, I put blue coloring in this to make us know this is saltwater. Saltwater in the actual bay is not blue... We're going to be using these two colors to see what happens when we mix them together (Y4 Harry Video 1.5).

In this example, Harry understood the need to support students in identifying the aspects of the natural world that are represented by a model by explaining how the model is similar and different from the natural world.

Overall, the teachers' lower KCT scores were not surprising, because this science practice was minimally supported in their teacher education program (see Chapter 4). The minimal opportunities to learn about scientific modeling in the teacher education program may have led the novice elementary teachers to draw on their understanding of the other science practices to inform their understanding of scientific modeling. This could have been why the teachers demonstrated inconsistencies in their sensemaking about scientific modeling.

Asking Scientific Questions. There were few instances where the teachers engaged their students in asking scientific questions. For this reason, the analyses are based on open coding of the few instances to determine the teachers' CCK and KCT for this science practice. In general, the teachers struggled to understand this science practice (i.e., their CCK was poor). The teachers did not typically distinguish between scientific questions and investigation questions. This was not surprising since the Elementary Science Methods course focused on asking investigation questions and it was not explicit as to how investigation questions related to the science practice of asking scientific questions. The teachers did, however, understand the role of scientific questions in science more broadly. Diana demonstrated this when she said, "the whole purpose

of science, you know, asking questions about the world around you, thinking through all these phenomena that can be observed and ones that can't be observed (Y4 Diana Interview 3).

The novice teachers also struggled with how to construct scientific questions themselves. In particular, they had difficulty knowing how to determine the specificity of the question for guiding scientific investigations. Claudia mentioned this in her interview after the Elementary Science Methods course when she said,

We did talk about our investigation question because...I came in with a question [about] how broad or narrow to make [the investigation question]. Or not narrow, but specific to the lab... And it's something that you collect evidence to be able to answer... But I didn't know if it should be... much broader, abstract concept that they would investigate (Y2 Claudia Interview 1).

Overall, the teachers' KCT related to asking scientific questions tended to be more teacher-centric. The teachers (or curriculum) typically created and asked the investigation questions instead of the students. Though all the teachers knew that students should ask their own scientific questions only Claudia and Diana minimally demonstrated this during their teaching. For example, during Claudia's second-year teaching she provided students with a "Wonder Wall" to post their science questions related to the unit on ecosystems, food webs, and life cycles. She also provided time during a science lesson for students to search various resources for answers to their questions. Even with this experience, though, it was not evident that she understood how to support students in constructing their own scientific questions to guide investigations. When asked about this, Claudia said,

Ultimately, like, shifting the science toward introducing a topic, then asking questions, and then kind of coming up with an investigation that would answer it. But, I'm not there

yet with my teaching. But, that's the ultimate goal, and that's really what, like, the new standards are pushing us towards too (Y3 Claudia Interview 3).

This difficulty in understanding how to help students ask scientific questions was consistent across all three teachers. Diana even discussed the challenges students have with asking scientific questions,

[Students] get really caught up in questions that really aren't going to lead us to where we need to go and for them to be able to determine, like, is this a question worth pursuing or not was very challenging... But it was hard distinguishing between is this actually going to help us further our learning on this topic whereas this other topic could be very interesting and engaging, but how are we directing it to that testable question (Y4 Diana Interview 3).

Even though Diana could articulate the challenges students had with constructing scientific questions, she did demonstrate an understanding of how to support students in constructing scientific questions.

Obtaining, Communicating, and Evaluating Scientific Ideas. Similar to asking scientific questions, there were few instances when the teachers engaged their students in obtaining, communicating, and evaluating scientific ideas, and so I open coded these instances. Overall, the teachers' understanding of this science practice tended to be limited and superficial. For example, Harry mentioned this in the interview after the Elementary Science Methods course when he said,

And implicit in [science learning] is always communicating and evaluating and obtaining information because I feel like they're very used to having to do that, especially the school... it's always—in everything we do is communication (Y2 Harry Interview 1).

Harry's understanding of this science practice was limited to the name of the science practice. He was not able to articulate any nuances in what each part of the science practice means or how to engage students in this science practice.

When the teachers did engage their students in using science texts, they tended to do so for the purposes of gathering information to inform the scientific investigations. They knew that scientific texts were used for "obtaining" scientific information, but their understanding of how to use the texts tended to be on reading levels and less on knowing how to help students scientifically engage with the texts.

In contrast, Claudia was the only teacher who engaged her students in investigating with text during her second-year teaching. Claudia began the lesson by saying,

So what I wanted to do today is to actually figure out, what the heck it means to actually be living... On Google Classroom, you have a question... that asks you, 'What does it mean for an organism to be a living thing?'... 'And how do we know if something is alive?'... You're going to spend five minutes seeing what you can figure out. You're going to look for the definition, examples and characteristics, and then you are going to comment with what you found...The things you're going to add onto Google Classroom is new information that you think is valuable for the class (Y4 Claudia Nutrient Systems Video 2.1).

In this example, Claudia understood the need for her students to evaluate the texts they were using in order to obtain information that could be used to inform their work around living things. She followed up the students' group work with a whole class discussion to determine patterns in how the different sources were characterizing "living things." The patterns were used to construct a class list of the main characteristics of living things. In this way, she knew to have

students evaluate the texts for the purposes of obtaining information that would inform their work about living things. This type of nuanced understanding of this science practice was only evident in Claudia's instruction in her second-year teaching.

Overall, the teachers rarely engaged their students in this science practice and when they did, it was more teacher-driven and their understanding superficially related to how they made sense of the words, "obtaining," "evaluating," and "communicating information." The teachers' limited and superficial understanding was not surprising since the Elementary Science Methods course did not provide opportunities to learn about this science practice and how to support students in obtaining, evaluating, and communicating information (see Appendix N).

Relationships Across Dimensions of the Science Practices

This section outlines the relationships across every dimension of all six of the science practices and how the teachers made sense of them. I compared the mean scores of the teachers' understanding of every dimension to identify any patterns in their sensemaking. The intent was to identify dimensions where novice elementary teachers may need further support.

Overall, there was greater variation in the teachers' CCK of the dimensions of the science practices (see Figure 5-8) compared to their KCT (Figure 5-9). With regard to their CCK, the dimensions of scientific explanations and arguments were strengths in the teachers' understanding. Similarly, there was a strong understanding that scientific observations are used as evidence. In comparison, the teachers struggled with understanding that models represent visible and invisible aspects of the natural world and that they should be used to test predictions. The teachers also struggled with understanding variables and controls as part of scientific investigations and that analyzing and interpreting data involves gathering consensus across analyses.

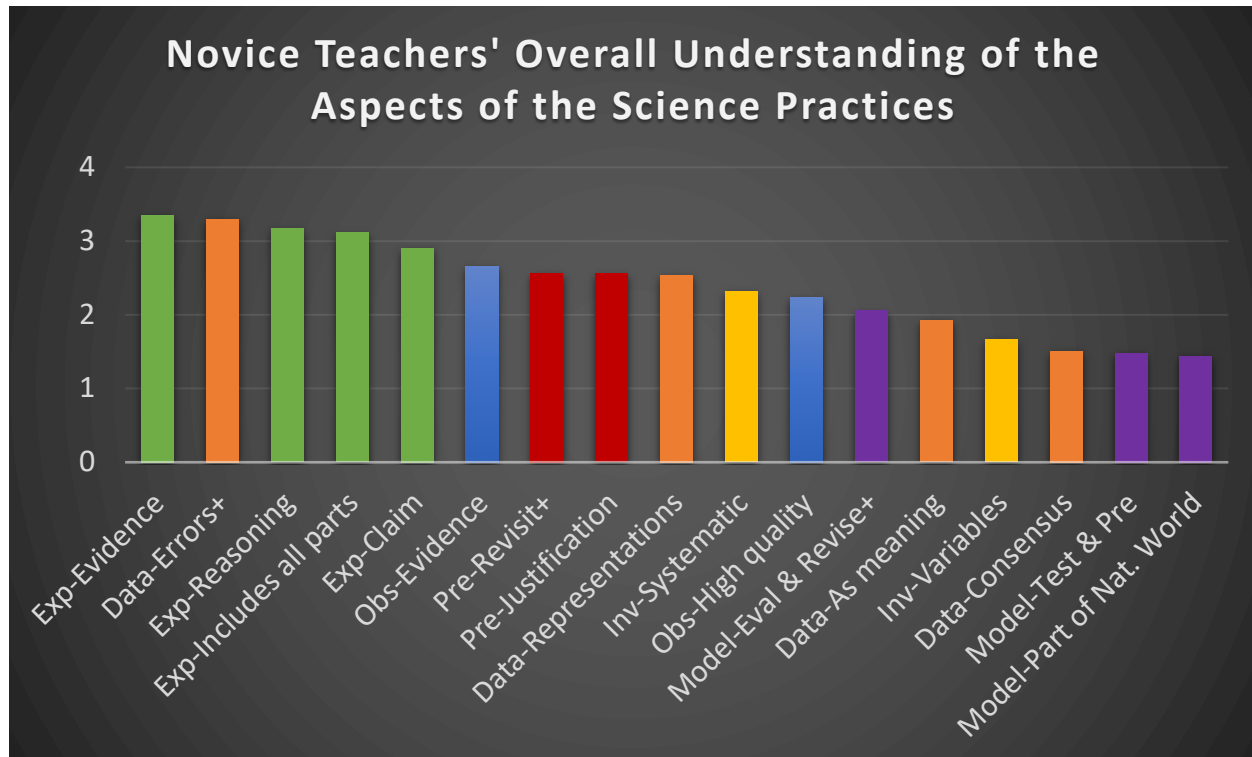


Figure 5-8. Novice elementary teachers' CCK of the dimensions of the science practices (Green represents dimensions of scientific explanations and arguments; Orange represents dimensions of analyzing and interpreting data; Blue represents dimensions of scientific observations; Red represents dimensions of scientific predictions; Purple represents dimensions of scientific modeling; and Yellow represents dimensions of scientific investigations. +Lower frequency of the dimension in the novice elementary teachers' science teaching practice)

The strengths the teachers demonstrated in understanding the dimensions of scientific explanations and arguments was not surprising because these science practices were the focus of their Elementary Science Methods course. In comparison, the Elementary Science Methods course also supported the teachers' understanding of high-quality scientific observations, which turned out to be more challenging for the teachers.

The dimensions of KCT for the science practices, however, had less variation (see Figure 5-9). The greatest strength was the teachers' understanding that students should be doing the

intellectual work and not the teacher. This dimension was strongest for all science practices. The teachers also demonstrated strength in understanding how to prompt students for patterns in data, model the investigation, and to circulate and ask sensemaking questions during investigations. Even though the teachers struggled in demonstrating understanding of the dimensions of science investigations (their CCK), they still could demonstrate how to engage students in science investigations. The teachers struggled most with their understanding of how to use models to explain phenomena, to discuss the parts of a model that represent the visible and invisible aspects of the natural world, and to support students in evaluating and revising models.

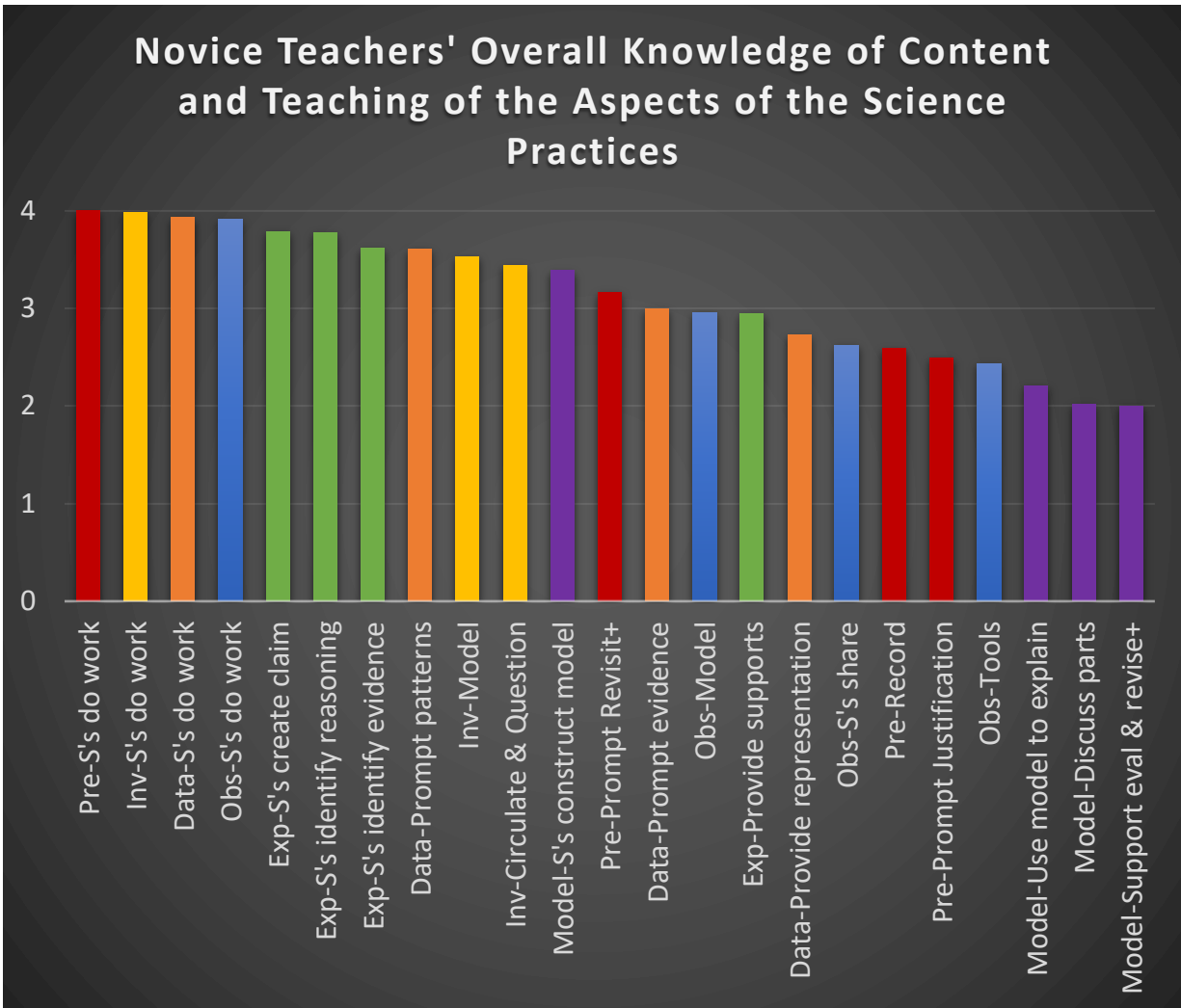


Figure 5-9. Novice elementary teachers' KCT of the dimensions of the science practices
 (Green represents dimensions of scientific explanations and arguments; Orange represents dimensions of analyzing and interpreting data; Blue represents dimensions of scientific observations; Red represents dimensions of scientific predictions; Purple represents dimensions of scientific modeling; and Yellow represents dimensions of scientific investigations.
 +Lower frequency of the dimension in the novice elementary teachers' science teaching practice)

The strengths in these teachers' understanding of particular dimensions of science practices indicates the potential of "readiness" for understanding the science practices. With regard to their CCK of the science practices, there are some dimensions that may be easier for these novice elementary teachers to make sense of in their teaching. These dimensions may serve

as a type of “readiness” for understanding the science practices. Smithey (2008), building on the idea of young children’s “reading readiness” (Farr & Anastasiow, 1969), explains PCK-readiness as a “collection of ideas” that, over time, will become more connected as novices develop their teaching practices (p. 27). When applying this idea to the science practices, the novice elementary teachers may have a “science practice-readiness” for beginning to make sense of the science practices. In particular, for the novice teachers in the current study, this may include understanding what constitutes as evidence in science and how evidence is related to claims and reasoning in explanations and arguments as shown by these teachers’ strong understanding of those dimensions.

Also, these teachers’ KCT of the dimensions of the science practices may serve as another part of their “science practice-readiness.” As these novices began thinking about their work with students, developing an understanding that students should be the ones doing the work of science may be a precursor to understanding more complex dimensions of KCT of the science practices. Perhaps when these teachers feel confident in their KCT of the science practices will they be able to confront their more limited CCK of the dimensions of the science practices. This is another way that the dimensions of KCT of the science practices could be part of “science practice-readiness.”

Overall, the novice elementary teachers in the current study demonstrated variation in how they understood the dimensions of the science practices, as well as the other sub-domains of content knowledge for teaching science. Across all of the sub-domains, their knowledge of the science concepts and practices, and how to teach the concepts and practices were most evident in their science teaching. The next chapter builds on the current and previous chapter by outlining

the trajectories of these teachers' CKT-S and opportunities to learn across the four years, as well as the nuances of how their knowledge was evident in their teaching practice.

Chapter 6 Trajectories of Novice Elementary Teachers' Opportunities to Learn and Their Content Knowledge for Teaching Science

This chapter responds to the research question stating *How do the learning opportunities for developing content knowledge for teaching science in the teacher education program and the school contexts compare to the novice elementary teachers' content knowledge for teaching science?* I reviewed the findings across the previous two chapters and organized the findings based on each teachers' opportunities to learn and their content knowledge for teaching science. Across the three teachers I found that the sub-domains of the teachers' pedagogical content knowledge were supported in similar ways across the four years. Also, the teachers' pedagogical content knowledge was most evident in their practice across the four years. Specifically, knowledge of content and teaching was most supported in the opportunities to learn and most evident in the teachers' practice.

All sub-domains of the teachers' subject matter knowledge were minimally supported across the four years among the opportunities I studied, except for some opportunities to learn about the science practices during the Elementary Science Methods course in year 2. The opportunities to learn that were studied for this dissertation were those in the coursework in the Teacher Education program related to science education. During the teaching experiences, the opportunities to learn were determined based on what the teachers said during interviews and on surveys, as well as interviews with mentor teachers and principals. The opportunities to learn did not include those in coursework outside the teacher education program or other experiences in

the school contexts (e.g., professional development). Also, I was unable to represent variation in the grain size of the different opportunities to learn (e.g., no distinction between time or influence of a discussion in a course compared to a professional development experience). Even though there were few identified opportunities supporting the teachers' subject matter knowledge, the teachers' core content knowledge of the science concepts was regularly evident in their teaching practice across the four years. Similarly, their knowledge of the science practices was regularly evident in their teaching practice beginning in year 2 when they experienced the most opportunities to learn about the science practices and how to engage students in them.

I discuss the relationships between the opportunities to learn and the teachers' knowledge in more detail in the following sections. The next section provides an overview of the novice elementary teachers' trajectories of knowledge and learning opportunities across the four years. To represent the teachers' trajectories, I use figures that reflect the CKT-S framework for each teacher over time.

Each figure is made up of an inner oval and an outer oval. Similar to Figure 2-3 (the CKT-S framework diagram), the inner oval represents the teacher's CKT-S that was evident in their teaching practice. The outer oval represents the opportunities to learn. As in Figure 2-3, the inner oval is divided into sections representing the eight sub-domains of CKT-S and the outer oval is divided into the same sections, corresponding to each sub-domain. The sections are then shades of green. For the inner oval, the shades represent to what extent that sub-domain of knowledge was visible in the teacher's practice during that time period. Light green indicates that the sub-domain was infrequently visible (0-33% of the coded segments), medium green indicates a mid-level of visibility (34-65% of coded segments), and dark green indicates that the

sub-domain was visible in the teacher's practice most of the time (66-100% of coded segments). Similarly, for the outer oval, the shades of green represent how prominent the opportunities to learn were for that sub-domain of knowledge. Sections shaded light green show that few of the opportunities to learn focused on that sub-domain (0-33% of the coded segments). Medium green indicates a mid-level of focus (34-65%), and dark green indicates a strong focus on that sub-domain during the opportunities to learn that occurred during that year (66-100%).

By comparing the shading of a sub-domain in the outer oval (opportunities to learn) with the same sub-domain in the inner oval (CKT-S), we begin to see relationships between how the sub-domain was supported and the evidence of that knowledge in each teacher's practice. For each teacher, there are four figures with each representing knowledge and opportunities in each year. Looking across all four figures demonstrates the trajectories of each teacher's CKT-S and opportunities to learn.

Novice Elementary Teachers' Trajectories of OTL and CKT-S

The novice elementary teachers were fairly consistent across the four years with, in general, minimal to moderate CKT-S and opportunities to learn (see Figure 6-1). All three teachers demonstrated moderate to high evidence of their knowledge of the science concepts (CCK: Science concepts) across the four years (medium and dark green shading in the inner ovals). And they all had minimal opportunities to learn about the science concepts across the four years (light green shading in the outer ovals). All teachers also drew on their knowledge of the science practices (CCK: Science practices) once they had opportunities to learn about the science practices in the Elementary Science Methods course during year 2, with medium or dark green shading for the inner oval for Years 2, 3, and 4.

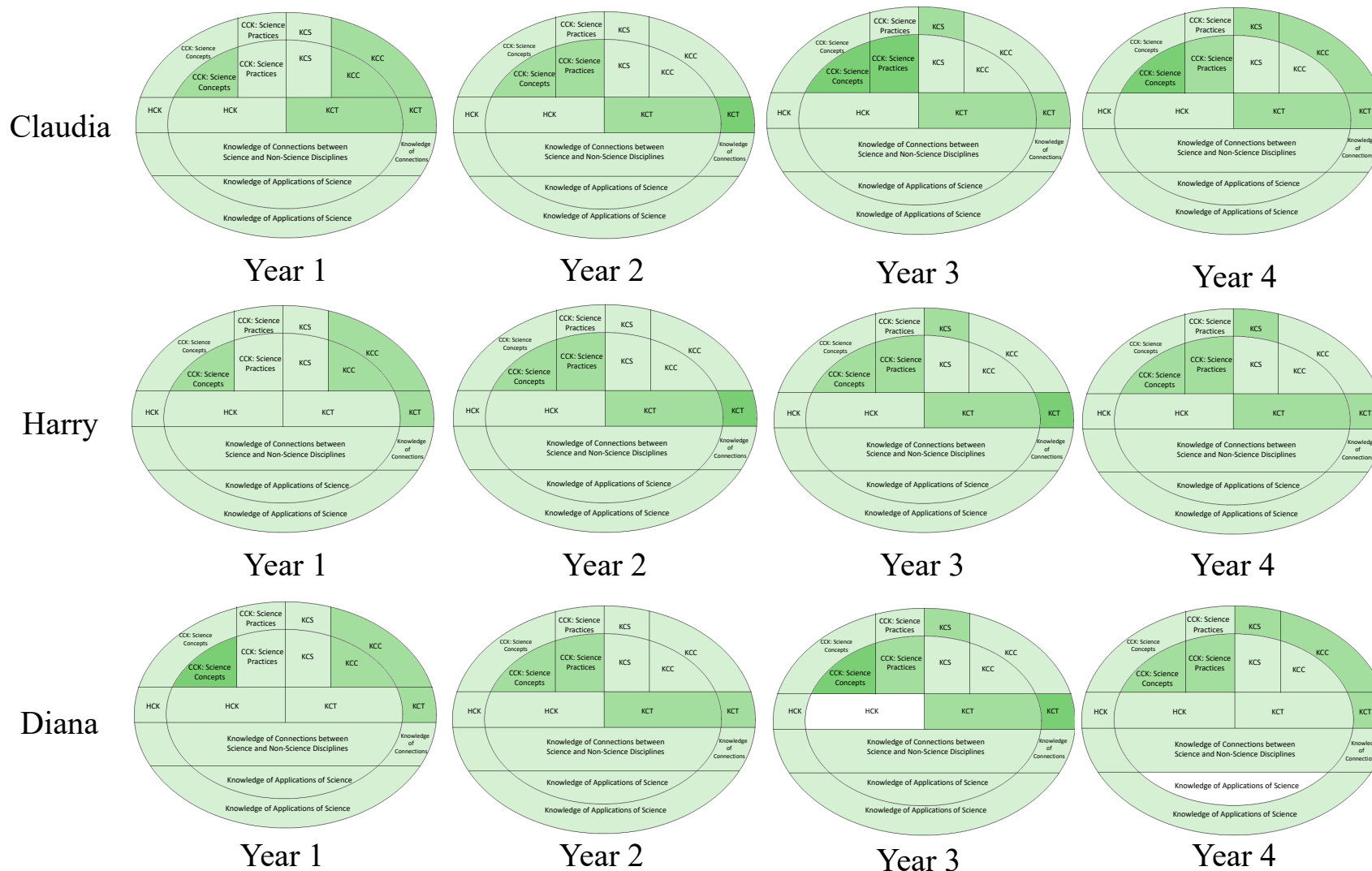


Figure 6-1. Trajectories of CKT-S and Opportunities to Learn for Claudia, Harry, and Diana Across Four Years (For Diana, blank segments mean there was no evidence of knowledge of the particular sub-domain)

Beginning in Year 2, all teachers demonstrated moderate knowledge of content and teaching (KCT) (medium green shading in inner oval), except for Diana who demonstrated minimal KCT in Year 4 and Claudia who demonstrated moderate KCT in Year 1. The teachers also had moderate to high percentages of opportunities to learn KCT across the four years with slight variations between teachers, as represented by medium and dark green shading in the outer ovals. For example, Claudia and Harry mentioned slightly more opportunities to learn KCT in Year 2 and, similarly, Harry and Diana mentioned slightly more opportunities to learn KCT in Year 3 – indicated with dark green shading. Across all four years, Claudia also consistently drew on her knowledge of content and teaching (KCT) with opportunities to develop her KCT during each year. There were more opportunities to learn how to teach science in Year 2, which was not surprising since that was when the teachers took the Elementary Science Methods course – the main experience for learning how to teach science

Also, when the teachers had the greatest percentage of opportunities to develop their knowledge of content and curriculum (KCC) in the Teaching with Curriculum Materials course, this knowledge was most evident in their teaching practice, as indicated by medium green shading in Year 1. Claudia and Diana did have some opportunities to learn KCC in Year 4 (see medium green shading in outer ovals), but their knowledge was minimally evident in their teaching practice at that time (see light green shading in inner ovals). All three teachers also had moderate opportunities to develop their knowledge of content and students (KCS) during Years 3 and 4, as indicated by medium green shading in the outer ovals. They also had some opportunities to learn KCS in their Children as Sensemakers course in Year 1. Even with those opportunities to learn, their KCS was minimally evident in their teaching practice across all four years (see light green shading in inner ovals).

Lastly, the teachers' horizon content knowledge (HCK), knowledge of the connection of science to non-science disciplines, and knowledge of the applications of science was minimally evident with minimal opportunities supporting those sub-domains, as well. The only variation was the lack of any evidence of Diana's HCK and knowledge of the applications of science in Years 3 and 4, respectively.

Overall, the three teachers demonstrated similar trends in their CKT-S over time with similar opportunities to learn, even though they taught in different schools.

The following sections begin with an explanation of how each teacher's CCK and KCT of the science practices related to the opportunities to learn about the science practices in the Elementary Science Methods course. These relationships are unpacked in the following sections using a vignette and subsequent discussion of the nuances of how each teacher's knowledge was evident in their teaching practice and how they were supported to develop that knowledge. Using the teachers' responses during interviews about their strengths and challenges, I end each case with a discussion of how their knowledge was evident in their teaching practice and what their stated challenges mean for supporting other novice elementary teachers in developing knowledge in and for teaching science.

Each teacher is a case of how specific aspects of CKT-S relate to similar opportunities to learn that illustrate what was most prominent for each teacher. Claudia is a case of how her knowledge and opportunities about science discussions could leverage ways to engage students in analyzing and interpreting data. Harry is a case of how understanding how to engage students in a science practice can overcome limitations in understanding the practice itself, particularly when provided supportive opportunities to learn. Diana is a case of how knowledge of content and students informs teaching practice even with moderate support for doing so and minimal

evidence of the knowledge in teaching practice. Except for the slight differences between perceptions of their knowledge and practices in teaching science, the teachers were relatively similar in how their knowledge was evident in their practice and in the opportunities they had to develop their knowledge across the four years.

Claudia's Trajectories of CKT-S and Opportunities to Learn

Claudia's strength in understanding how to engage students in analyzing and interpreting data, explanations and arguments, and investigations were also the science practices most supported in the Elementary Science Methods course. This is indicated in Table 6-1 by the greater percentage of opportunities to learn about those science practices and Claudia's higher mean scores. Specifically, she drew on her understanding of how to engage students in sensemaking discussions and her understanding of analyzing and interpreting data to inform how she led the sensemaking discussions, as discussed in the following section. Overall, Claudia's strengths in understanding how to engage students in the science practices – particularly explanations and arguments, investigations, and data analysis – reflected the focus of the Elementary Science Methods course.

Table 6-1. Claudia's Opportunities to Learn, CCK, and KCT of the Science Practices

Science Practices	Opportunities to Learn CCK ⁺	Claudia's CCK ⁺⁺	Opportunities to Learn KCT ⁺	Claudia's KCT ⁺⁺
Investigations	2%	2.73	9%	3.65
Predictions	0.6%	2.65	2%	3.03
Observations	0.9%	2.60	7%	3.05
Analyzing and Interpreting Data	3%	2.28	9%	3.46
Explanations & Arguments	11%	3.30	13%	3.64
Modeling	3%	2.26	0.6%	2.95

⁺The numbers represent the percentage of the total opportunities to learn in the Elementary

Science Methods course that supported each science practice

⁺⁺The numbers are the mean scores for Claudia's knowledge of each science practice across all four years. The maximum score possible is 4.00 and the minimum score possible is 1.00.

Strengths of Claudia's CKT-S and Opportunities to Learn. Discussions provided a way for Claudia to support students in constructing knowledge and engaging students in science practices, specifically analyzing and interpreting data, scientific explanations, and argumentation. Using discussions in science was also a focus of how Claudia saw herself supporting science learning (Claudia Y2 Interviews 1 and 2; Y3 Interview 1; Y4 Interview 3). Though only 10% of the opportunities to learn KCT in the Elementary Science Methods course supported knowing how to engage students in science discussions, the focus of the Elementary Mathematics Methods course (taken concomitantly) was on leading discussions. That course, however, was not analyzed for my study. Even with the minimal opportunities in the Elementary Science Methods course, using discussions had a large impact on Claudia's understanding of how to teach science. She mentioned that

I would say in terms of the sensemaking, it was really focusing on the conversations and the discussion, like, having lots of discussion around the investigations and what they were seeing and what they were learning and what they were thinking and addressing misconceptions (Claudia Y4 Interview 3).

She connected her understanding of how to engage students in science discussions with her understanding of the science practices to support students' knowledge construction. To demonstrate these connections, I turn to a vignette of a lesson Claudia taught in year 3 where she engaged students in analyzing data about pendulums to determine the variable that caused a pendulum's swing to change.

Claudia's Vignette. After directing students to the data table and the pendulums hanging at the front of the class, Claudia began the discussion by asking, "What were we able to conclude from the last class?" (Claudia Fall Video 7.1). After a student responded, Claudia pushed the students further by asking, "How did we figure out, from this data table, that conclusion? What were we looking at – I know you were looking at patterns, but how do I know that that is true from that data table?" A student responded and Claudia repeated it saying the pendulum swings changed when the length of the pendulums changed. Claudia then said, "We are going to put our data into a graph" and had a short discussion about the usefulness of graphs for analyzing data. The class then developed graphs of the class data (Claudia Fall Video 7.1).

After graphing, Claudia directed students to identify outliers in their data by asking, "why do those [data points] seem out of place?" After a student responded Claudia explained that the student was comparing a data point to other data points around it. Claudia then asked what might have happened to get the outlier data point. The discussion continued with students providing possibilities for the outlier data. Once ideas were suggested, Claudia moved the data analysis

discussion forward by having students identify a “smooth line that goes through most of [the] data points” in order to identify trends in the class data. She then had students make and share predictions of the number of swings for pendulums with longer lengths. The class then tested those predictions and discussed whether their findings for this longer pendulum were reasonable in relation to the “smooth line” they created. After the students agreed on the reasonableness of the data, she ended the discussion by emphasizing that they used the graph to “see where the point might fall,” highlighting the importance of graphs for analyzing and interpreting data (Claudia Fall Videos 7.1 and 7.2). Later, she had the students constructing claims supported by evidence from their graphs in response to the question about what caused the pendulum swing to change.

In this vignette, much of the scientific sensemaking work that the students were doing occurred during science discussions. Claudia used her understanding of how to engage students in science discussions to support them in learning how to analyze and interpret data using a data table and a graph. In year 2, the Elementary Science Methods course provided opportunities to learn how to do this. For example, during that course, after the novice teachers engaged in rehearsals with small groups the teacher educator said,

[Let’s identify] strong teacher moves that you saw or that you felt like you engaged in, because a lot of you were engaging in really strong teaching...What were some strong teacher moves that you saw that helped students identify patterns and trends in data? (Y2 ESM Video 7.2).

The novice teachers then identified many ways to support students in doing this through the use of discussions. A few ways that came up were to have students comment on one another’s ideas, ask questions in different ways, and remind students to refer back to their evidence to support

their ideas (ESM Video 7.2). Though the vignette of Claudia's teaching was from the year after she was in the Elementary Science Methods course, there is evidence of similar practices: she had students comment on one another's ideas, she asked questions in different ways, and she prompted students to refer to the data as evidence for supporting their ideas. Claudia also focused on the use of representations for analyzing data, which was something she mentioned during the whole class discussion in the Elementary Science Methods course (Y2 ESM Video 7.2).

More than just asking students questions, Claudia knew to prompt students for patterns in the data demonstrating her understanding of how to question students to make sense of the data. She also demonstrated an understanding of the importance of representations for analyzing and interpreting data and of how to engage students in using those representations for scientific sensemaking. In this vignette we see Claudia's strong knowledge of the dimensions of analyzing and interpreting data and how to engage students in doing so paired with her understanding of how to engage students in science discussions. Her understanding about discussions also came out during interviews when she said,

I think that it's important that the students are at the center and they're the ones initiating it through discussion and teaching each other because that's how they really are going to learn it (Claudia FYT Fall Interview).

Claudia understood the importance of engaging students in scientific sensemaking. Though the opportunities to learn about science practices and how to engage students in science discussions occurred in the teacher education program, those opportunities provided a foundation for Claudia to continue developing her knowledge during her first few years of teaching.

Challenges of Claudia's CKT-S and Opportunities to Learn. When considering limitations of the opportunities to learn and Claudia's CKT-S, Claudia mentioned being less comfortable with understanding students' alternative ideas in science. For example, she said,

I think [students] bring up things that you can never fully be prepared for. And since it's my only--second time teaching it, it's like, wow. I've not heard that one before. I think after ten years of teaching it, you're like, "Oh, I've heard that. I'm prepared to answer that." (Claudia Y4 Interview 1).

Claudia's knowledge of content and students was minimally evident in her teaching practice across the four years. Only 25-28% of the coded segments had evidence of Claudia drawing on her KCS, as evidenced by the light green shading for that sub-domain of the inner oval in Figure 6-1. There were also infrequent opportunities to develop KCS across the four years. Approximately 28% of the opportunities to learn in the teacher education program supported the teachers' knowledge of content and students (see light green shading in the outer oval), which – for Claudia – were more than in the first two years of teaching. The opportunities that did support Claudia's KCS, though, emphasized students' strengths and challenges with science concepts which was similar to how she thought about students and science. For example, Claudia wrote in her lesson plan on heat energy transfer during the Elementary Science Methods course,

In this experiment students are tracking the transfer of energy, which is an abstract concept because it has no mass and does not take up space. Students may have a difficult time understanding that even though energy is not matter, it can still be measured. (Y2 Claudia Lesson Plan 1).

Not only did Claudia primarily attend to students' challenges with the science concepts, the opportunities to learn also mainly focused on this aspect of KCS.

Claudia also tended to connect her understanding of students' alternative ideas with her comfort with the science concepts (her CCK: Science concepts). For example, she said,

I feel comfortable because if I don't know the answer, I'm not afraid to tell them that. And I want them to know that I'm learning and gaining knowledge with them... You're always going to end up with things that you just don't know. And it's like, I'm not going to make that up because there's facts. There's truth. And there's evidence out there. And so, I'm really comfortable with it, whether I know the answer or not. And I do feel very competent in my science knowledge (Y3 Claudia Interview 3).

In this quote, Claudia connected her knowledge of students' ideas with her knowledge of science. Again, since most of the opportunities to learn focused on students' ideas in science, it seems reasonable that Claudia related this to her understanding of science concepts, as well. Overall, Claudia's limited knowledge of content and students evident in her practice across the four years and the fewer opportunities to learn demonstrate areas in which further support and knowledge development are needed.

Claudia was a case of how novice elementary teachers relate sub-domains of their CKT-S to one another – specifically her KCS with CCK: Science concepts, as well as her knowledge of how to engage students in science discussions with how to analyze and interpret data. Both reflect the opportunities to learn CKT-S throughout the four years. As Claudia mentioned, though, opportunities to learn in other disciplines (i.e., Elementary Mathematics Methods) can also inform knowledge for how to teach science.

Harry's Trajectories of CKT-S and Opportunities to Learn Over Time

As mentioned above, the main opportunities to learn about the science practices occurred in the Elementary Science Methods course, which was also when Harry's knowledge of the science practices became more evident in his practice. Along with knowing about the science practices, the course also focused on how to teach the science practices (KCT of the science practices). Similarly, Harry's KCT was more evident in his practice once he experienced those opportunities. As Table 6-2 demonstrates, most of the opportunities to learn supporting the science practices focused on scientific explanations and arguments. Harry scored the highest in his understanding of those science practices, as well as fairly high in his understanding of how to teach those science practices. In contrast, he scored the highest in understanding how to teach about scientific investigations, but the lowest in understanding what scientific investigations are. The opportunities to learn similarly focused on KCT for scientific investigations more than CCK for scientific investigations. Harry discussed this science practice as being important for his science teaching, which is discussed in more depth in the following section.

Table 6-2. Harry's Opportunities to Learn, CCK, and KCT of the Science Practices

Science Practices	Opportunities to Learn CCK ⁺	Harry's CCK ⁺⁺	Opportunities to Learn KCT ⁺	Harry's KCT ⁺⁺
Investigations	2%	1.53	9%	3.80
Predictions	0.6%	2.00	2%	3.11
Observations	0.9%	2.25	7%	2.94
Analyzing and Interpreting Data	3%	2.17	9%	3.07
Explanations & Arguments	11%	3.24	13%	3.61
Modeling	3%	2.96	0.6%	3.41

⁺The numbers represent the percentage of the total opportunities to learn in the Elementary

Science Methods course that supported each science practice

⁺⁺The numbers are the mean scores for Harry's knowledge of each science practice across all four years. The maximum score possible is 4.00 and the minimum score possible is 1.00.

Strengths of Harry's CKT-S and Opportunities to Learn. The Elementary Science Methods course was designed to support novice elementary teachers in learning how to engage students in conducting scientific investigations. Doing so involves collecting data to use as evidence when constructing scientific explanations and arguments. Harry took up this focus on investigations as important for scientific sensemaking when he said during an interview in year 4,

It's a combination of giving the structure and the environment for this inquiry, but then also giving [students] space to be able to implement their actions. Instead of giving them the steps for the investigation, helping them decide what the best investigation would be or helping them think through how they would find the answer to that question, often leading them to an investigation that I've already planned, but helping them think through

those steps that I would have done or a curriculum developer would have done. Like, helping them think through those steps is really helpful for their sensemaking (Y4 Harry Interview 3).

Harry recognized the importance of having students conduct an investigation, as well as think about how to plan an investigation in supporting their scientific sensemaking.

Harry's understanding focused more on how to engage students in conducting the investigation (KCT) and less on the dimensions of a scientific investigation (CCK). Similarly, the Elementary Science Methods course focused more on KCT for scientific investigations than CCK of the practice. Even though Harry was not as comfortable with conducting scientific investigations, specifically managing all of the moving pieces, he still demonstrated strong understanding of how to do so during his teaching. The following vignette illustrates this.

Harry's Vignette. During year 4, Harry taught a unit on a local watershed. The students created a model of the local watershed and used it to investigate, *What happens when fresh water meets saltwater?*. First, he had students predict what they think would happen when the fresh water and saltwater mix in the model watershed. Next, Harry engaged his students in a discussion about possible observations of the two different types of water in the watershed. Third, he led a discussion about how to record observations by saying, "When scientists do experiments like this, they need to be watching so closely to see what happens." He also explained how to conduct the investigation without demonstrating it, because doing so would give away the results of the investigation. While explaining how to conduct the investigation, Harry periodically made connections between the model the students were using and the natural world. He then passed out the materials and the students conducted the investigation (Y4 Harry Video 1.3).

While students were working, Harry circulated from group to group answering and asking questions. He asked questions about what the students noticed, their ideas about why the results occurred the way they did, and how what they observed related to the phenomena in the local watershed. In some groups, the water was not flowing because the containers were elevated incorrectly. When Harry realized this issue, he circulated to each group giving suggestions for adjusting the containers to get accurate results while also asking the students sensemaking questions. After the students conducted the investigation, he pulled the class back together to have them focus on recording their observations by saying,

Right now, I want us to focus on what you saw – what happened, what could your eyes see when you poured in the water. Think about what you poured in that first half of the water and what happened when you poured in the rest of the water. Even if you think you messed it up still talk about what you saw. We are going to do this silently and independently because I want to see what you saw and then you're going to be able to compare what other people at your table saw and what the whole class saw (Y4 Harry Video 1.3).

After the students recorded their observations, they shared them with their table groups and the whole class to come up with a co-constructed scientific explanation about what happens when fresh water and saltwater mix in a watershed (Y4 Harry Videos 1.3 and 1.4).

In this vignette, Harry drew on his understanding of science predictions, observations, and investigations. When zooming in on his understanding of science investigations it was apparent that he understood how to model an investigation without giving away the results, as well as how to circulate to groups to ask scientific sensemaking questions. Not only was his strong knowledge of the dimensions of KCT for scientific investigations consistent throughout

his teaching, but it was also a focus in the Elementary Science Methods course. For example, during a class session the instructor prompted the novice teachers to notice – in a video of elementary science teaching – how another novice teacher used

Back-pocket questions. These are questions that [the teacher] had prepared in advance that she wanted to use as she was circulating around the room (Y2 ESM Video 4.2).

Using backpocket questions is a dimension of KCT for scientific investigations. Doing so was reinforced throughout the course when lesson planning, during rehearsals of science teaching, and in course readings (Y2 ESM Syllabus; Y2 ESM Instructional Planning Template; Y2 ESM Video 4.2; Y2 ESM Week 4, 5 slides; Y2 ESM Zembal-Saul et al., chapter 1).

In the vignette, Harry rarely talked about what scientific investigations are, which was typical for his science teaching practice. Even though he rarely talked about what they are and demonstrated minimal knowledge of the dimensions of CCK of scientific investigations, he was still able to develop and draw on his KCT of investigations during his teaching. Similarly, there were few opportunities in the Elementary Science Methods course that foregrounded the dimensions of scientific investigations (CCK) with more foregrounding the dimensions of KCT of investigations. Knowing how to engage students in scientific investigations provided the stepping stones for Harry's developing knowledge of scientific investigations.

Challenges of Harry's CKT-S and Opportunities to Learn. As a novice elementary teacher, Harry also demonstrated challenges in his CKT-S, which were reflected in his minimal opportunities to learn some sub-domains. Similar to Harry's varied understanding of scientific investigations, his understanding of the applications of science and his views on the applications of science differed from one another. During interviews, Harry frequently discussed the importance of the application of science stating,

Thinking about ways that you can authentically present the content of science... And then figuring out based on that research what's one way that we can put that research into action. And so it would definitely depend on the content and whether that could actually be implemented is another question as well...So how do they put what they know into action (Y2 Harry Interview 2).

In this quote, Harry understood the importance of applying science to other issues or phenomena, but he also recognized the challenge to do this with different concepts. Also, his notion of “putting content into action” requires knowing of social issues that potential content can relate to and how it relates. Often this involves knowing students in relation to the content (KCS), the content (CCK: Science concepts), and the social issues the content and students relate to (Kloser, 2014). As this demonstrates, having knowledge of the application of science is complex and involves knowing more than just one sub-domain of CKT-S.

Though Harry understood the importance of this sub-domain he demonstrated a more limited understanding in his science teaching practice. For example, in year 4, this knowledge was evident in only 16% of the coded segments, which was the greatest frequency and percentage for all teachers across all experiences. Similarly, knowledge of the application of science was minimally supported across the four years. The most support occurred in the Elementary Science Methods course through the use of the EEE Framework that guided the course. The framework – which structured investigation-based science lessons – included a section in the final “E” of a lesson to “apply knowledge to new problems or questions” (Y2 ESM PowerPoint slide 6). Yet, during a rehearsal in the course and in his teaching in the classroom, Harry ran out of time to “apply knowledge to new problems or questions” during his instruction (Y2 Harry Peer Teaching Video Explain; Y2 Harry Video 1.3). Even with this focus on the EEE

Framework, there were still minimal opportunities to learn overall, which were reflected in the minimal evidence of this knowledge in Harry's teaching practice.

Even with the minimal knowledge and opportunities to learn, Harry still discussed this as an important part of science teaching. He mentioned this again in his year 4 interview saying,

And so, I think it was really just seeing firsthand how we can influence this and how complex of an ecosystem it is. I think kids often times think a creek is just water. But it's so much more than that. And there's so many more things that depend on it. And so, to have trash flowing down that, or to have contaminated water or pave over it is a huge deal. And so, I think it helps them to connect that firsthand of how it actually looks. And so, we were able to actually refer back to that experience when we went on and completed the action project... Kind of taking advantage of the fact that it was so focused on our local environment means that we can actually take what we've learned and apply it in a real way (Y4 Harry Interview 2).

In this quote, Harry demonstrated the understanding that science learning is more meaningful and should be applied to local issues. That interview took place at the end of the watershed unit discussed in the vignette above. That unit was designed by a local non-profit organization to focus on watersheds by using a local environment that students could connect with. The unit ended with the students developing and enacting "action plans" to help protect the local environment (e.g., picking up litter, writing a letter to a local government board). Harry's quote demonstrates his understanding about the connections the unit made and the importance of helping students apply their understanding to social and political issues beyond the classroom.

The disconnect between Harry's perceived importance of the applications of science and his limited knowledge and minimal opportunities to learn indicate the need for further support to

understand this sub-domain. As Harry's case demonstrates, knowing that it is important to apply science concepts and practices to issues beyond the classroom may not be enough for novice elementary teachers to understand *how* to do so. Even though Harry demonstrated this knowledge the most of the three novice elementary teachers, he still struggled to draw on it in his science teaching practice. Harry's case demonstrates the complexity of the knowledge of the application of science and the need for further support to help novice elementary teachers develop this knowledge.

Harry's case also demonstrates that knowing how to engage students in a science practice (e.g., scientific investigations) may still be productive for engaging students in scientific sensemaking even with limited knowledge of the practice itself. He understood the importance of scientific investigations for supporting sensemaking even though he struggled to understand the dimensions of what investigations are (CCK). The opportunities to learn reflected this mismatch by supporting teachers' KCT of the science practices more than their CCK. Harry's case demonstrates the way knowing how to engage students in science practices (KCT) may be a form of science practice-readiness to understand what science practices are (CCK).

Diana's Trajectories of CKT-S and Opportunities to Learn Over Time

In the Elementary Science Methods course, Diana had some opportunities to develop her knowledge of the science practices and how to engage students in them, which was reflected in her moderate to strong knowledge (see Table 6-3). Though Diana experienced the most opportunities to learn about scientific explanations and arguments and how to engage students in those science practices, her knowledge of those practices was not as strong as her knowledge of other science practices. In particular, she understood scientific predictions and how to engage students in interpreting and analyzing data more than scientific explanations and arguments even

though she had less opportunities to learn about predictions and analyzing and interpreting data. This differed from Claudia and Harry who both demonstrated the strongest CCK of scientific explanations and arguments and KCT of scientific investigations. One possibility could be Diana's experiences teaching young children. Engaging them in constructing predictions is easier for young children and serves as entries into more complex science practices like argumentation (Arias et al., 2017; Duschl & Osborne, 2002). Diana's focus on students and, in particular, young students was apparent in how she discussed her science teaching. This is discussed further in the sections below.

Table 6-3. Diana's Opportunities to Learn, CCK, and KCT of the Science Practices

Science Practices	Opportunities to Learn CCK⁺	Diana's CCK⁺⁺	Opportunities to Learn KCT⁺	Diana's KCT⁺⁺
Investigations	2%	1.69	9%	3.52
Predictions	0.6%	2.86	2%	3.07
Observations	0.9%	2.31	7%	3.03
Analyzing and Interpreting Data	3%	1.94	9%	3.50
Explanations & Arguments	11%	2.79	13%	3.29
Modeling	3%	1.78	0.6%	2.80

⁺The numbers represent the percentage of the total opportunities to learn in the Elementary

Science Methods course that supported each science practice

⁺⁺The numbers are the mean scores for Diana's knowledge of each science practice across all four years. The maximum score possible is 4.00 and the minimum score possible is 1.00.

Strengths of Diana's CKT-S and Opportunities to Learn. Across the four years, Diana identified her KCS as a strength and focus of her science teaching. Even though her knowledge

was not as evident in her teaching practice as other sub-domains, she still focused on her understanding of her students throughout her teaching. For example, in her reflection on her teaching about displacement in the Elementary Science Methods course Diana said,

The diversity of student ideas and misconceptions is astounding and what is even more interesting is the reasoning behind their ideas and misconception. For example, I did not expect one of the students to keep coming back to the idea that the animals (and Mr. Archimedes) are causing the bathtub to overflow because they have bones (which make them heavy)¹³ and when I asked him about it later he told me that he had just been watching a television program about dinosaur bones and how heavy some of them are. This really connects with the idea that in order to teach for understanding, teachers need to know their students' background knowledge and beliefs in order to best teach them (Y2 Diana Reflection).

She also experienced various opportunities to learn about students' ideas in science in the Children as Sensemakers course and while she was teaching during the Elementary Science Methods course and Student Teaching.

When discussing students' ideas, she connected her knowledge of content and students with her knowledge of how to teach science by saying,

Figuring out student misconceptions, which ones are harder for students to learn or which ones are harder for me to teach and how to devise lessons to help students with those misconceptions and help them start grasping those topics (Y4 Diana Interview 3).

¹³ Diana taught a kindergarten lesson on displacement where the students listened to a book about "Mr. Archimedes" and his animal friends who took a bath together. As more friends joined the bath, the water overflowed the bathtub.

In this example, Diana explained that understanding students' challenges with science concepts (KCS) informed her understanding of how to teach the science concepts (KCT). This differed from Claudia who connected her understanding of students' ideas in science (KCS) with her own understanding of the science concepts themselves (CCK: Science concepts). Diana's connections of KCS and KCT is demonstrated during her teaching in the Elementary Science Methods course when she taught a lesson to kindergarten students on displacement.

Diana's vignette. When teaching young children, Diana used a combination of whole class carpet time and small group centers to help her students engage in scientific investigations. During her lesson on displacement, she began with her students at the carpet where she introduced the lesson by reading the book Mr. Archimedes' Bath (Allen, 1986). She then co-constructed the investigation question *Why does Mr. Archimedes' bath always overflow?* (Y2 Diana Lesson Plan 1; Y2 Diana Video 1). After having students share their predictions with justifications, which Diana recorded on chart paper, she explained that the students would conduct the investigation at centers (Y2 Video 1).

During centers, Diana began by having every student record their predictions (where they think the water will go when they drop golf balls into it). She said,

Draw your prediction here (Diana points to spot on the investigation sheet). Where do you think the water level... this is the water level... What will happen to the water level when I put a ball in? Draw what you think. This is where we start with it. Do you think it will go up, or down, or stay the same? (Y2 Diana Video 1).

After recording their predictions, Diana worked with the young students to drop the balls in the container of water and record their observations. After conducting the investigation, Diana brought the whole class together on the carpet for a sensemaking discussion.

Diana began the sensemaking discussion by reminding students of the investigation question and the students' initial predictions that she had recorded. She then asked, "what did we see when we put the golf balls in the water?" A student responded by saying that the water went higher, and Diana asked her why she thought it went higher. She then turned to a specific student (after referencing her notes) saying, "G I have a question for you. What changed? What made the water go up higher?" The students continued the discussion by recognizing that more golf balls caused the water to go up. She restated a student's idea saying,

The golf balls take up space. They take the space that the water was in and the water has to go up (Y2 Diana Video 1).

Diana then said they should test this idea. After moving to the water table, she asked the students, "Why does Mr. Archimedes' bath overflow? What happens?" A student responded about the balls in the water instead of referring to Mr. Archimedes and his friends. Diana then said, "We are putting balls in the jar, but what's going into Mr. Archimedes' bath?" A different student said the people go in and the water goes up and the balls go in and they go up. Diana clarified whether the student meant the water goes up or the balls go up. When the student agreed that it was the water and not the balls, Diana then conducted the investigation again, but instead of referring to each ball as a "ball" she referred to each ball as "Mr. Archimedes," "kangaroo," "wombat," and a "goat" (Mr. Archimedes' friends). Diana then re-explained how all of the friends going in the bath caused the water to go up and eventually overflow the bathtub. To end the investigation, she worked with students during afternoon centers to write their scientific arguments as to why they thought Mr. Archimedes' bath overflowed (Y2 Diana Video 1).

In the vignette, Diana drew on her students' ideas to co-construct the investigation question and also attended to students' ideas when she recorded and revisited their predictions.

Diana's knowledge about the young students' challenges with the investigation were evident when she noted that the students were using the language of "ball" to answer the investigation question instead of "Mr. Archimedes' friends." She discussed this in an interview saying,

Then I was like, "So, why does Mr. Archimedes' bathtub overflow?" Blank stares. And I was like, "Okay, like one golf ball. Here is the goat. Two golf balls, here is the koala. Here is the wombat. Here's Mr. Archimedes." And I was like, "What happens when the last person gets in?"...They said Mr. Archimedes' bath overflows because there's too many friends. But when I asked them to add how do they know that with the golf balls, [they] couldn't make the connection (Y2 Diana Interview 1).

By prompting the students for evidence from the investigation, Diana was able to identify the challenges the students had with connecting the golf ball investigation to the story about Mr. Archimedes and his friends. Knowing how to prompt students in order to learn about their ideas was supported in the Children as Sensemakers course and the Elementary Science Methods course. For example, an interview protocol used in the Children as Sensemakers course said,

If you are unsure what the child is saying, ask the child to tell you more, or if there are specific ideas that you are unable to understand, say something like, 'Can you tell me more about...?' (Y1 CaSM Interview Protocol).

Similarly, the Elementary Science Methods course provided opportunities to learn how to prompt students for justifications with their predictions and evidence with their claims (e.g., Y2 ESM Syllabus; Y2 ESM Full Scale Science Teaching Assignment; Y2 ESM PowerPoint Week 4, 5, 6; Y2 ESM Reading Zembal-Saul et al., Chapter 4).

Diana's KCS was also evident in her lesson planning for teaching the displacement lesson. In her lesson plan, not only did she attend to students' alternative science ideas – as is

required by the lesson planning template (Y2 ESM Instructional Planning Template) – but she also wrote how she would respond to each alternative idea when planning her instructional sequence. For example, she wrote,

Possible student idea that could be disproved: *The water just appears*. Ask, “If more water appeared, what would happen to the water level after we took all the golf balls out of the jar?” Further prompt if needed: “Would the water level go back to where it started? Explain: “We observed that the water level went back to where it started so we know that no extra water appeared or was added.”...Work with the students to either disprove the remaining ideas, modify the remaining idea(s) so it/they are a scientific explanation, or explain how the idea(s) is/are correct using the evidence from the investigation (Y2 Diana ESM Lesson Plan).

In this example, she demonstrated an understanding of students’ challenge with understanding where the higher water level comes from and also an understanding of how to respond to that alternative idea – an example of her KCT. This quote and the vignette show how Diana’s KCS directly related to her KCT through the ways she responded (or planned to respond) to students’ alternative ideas. Overall, though Diana’s KCS was minimally evident in her teaching practice and moderately supported during years 1, 3, and 4, it still directly informed her science teaching practice.

Challenges of Diana’s CKT-S and Opportunities to Learn. When working with young children, Diana struggled to understand how to use scientific language in ways that supported their sensemaking – a part of her knowledge of content and teaching. Specifically, she talked about the challenges of using student-friendly language with young children that attends to their developmental level while also not leading to further misconceptions. In an interview, she said,

I don't want to invite the misconceptions with my instruction... I'm not familiar with this age. I don't know what is exactly--like I do not feel confident in what's developmentally appropriate for kindergarten (Y2 Diana Interview 2).

In this example, Diana discussed her challenge with understanding how to use scientific language with students, which came up again during an interview in year 3 (Y4 Diana Interview 3). As she was developing her teaching practice during the Elementary Science Methods course, Diana began working on this issue of knowing how to use scientific language. This was demonstrated in the vignette when she

- a) used language about how to make predictions and observations (e.g., "water going up"),
- b) explained displacement in developmentally appropriate ways (e.g., "The golf balls take up space" [Y2 Diana Video 1]), and
- c) attended to students' language use (e.g., "balls" instead of "Mr. Archimedes' friends").

Though she demonstrated this understanding in her instruction, she still worked to develop this knowledge throughout her teaching (Y2 Diana Interview 2; Y2 Diana Reflection; Y4 Diana Interview 3).

Diana's struggle with understanding how to use scientific language was also minimally supported in the Elementary Science Methods course. Only 9% of the opportunities to learn KCT supported this understanding. For example, the Elementary Science Methods course used a framework that incorporated issues of language when attending to issues of equity in science teaching. These were highlighted in class as,

Use language in accessible and accurate ways, and help students to do so (Y2 ESM PowerPoint week 1, 2, 3, 5).

Though minimally supported, the Elementary Science Methods course did call the novice teachers' attention to issues of language use, which was likely quite apparent for Diana who was teaching in a kindergarten classroom.

Also, Diana struggled with the understanding of when to introduce scientific language with students. This was apparent when she said,

I'm still trying to figure out if it's better to front load the vocabulary or not. For some of them, it is. I know now, Phenomenal Science [a science curriculum program Diana was using] is saying don't give it to them until after they have the experiences. So, kind of figuring out when is it helpful to give it to them ahead of time? When is it helpful to give it to them after they have the experience? (Y4 Diana Interview 3).

In this example, her struggle with understanding how and when to introduce scientific language was evident. Harry also struggled with understanding how to do this. He typically introduced the scientific language and concepts at the beginning of his science lessons, sometimes giving away the concepts introduced in the investigation (see vignette above) (Y2 Harry Video 1, Y2 Harry Video 2, Y3 Harry Spring Video 2.1, Y4 Harry Video 1.1, Y4 Harry Video 1.3). Claudia was similar in her use of science language at the beginning of investigations (e.g., Y2 Claudia Video 2.1; Y3 Claudia Fall Interview; Y4 Claudia Interview 1). With the challenges the novice elementary teachers face and the few opportunities to learn how to do this, further support is needed for helping novice elementary teachers understand how and when to introduce scientific language with their students.

Diana serves as a case of the importance of KCS for informing science teaching – even if it is less evident in teachers' practices. Diana was very attentive to students' challenges and ideas in science. However, she also struggled to understand how to introduce students, particularly

young students, to scientific language. She did not have many opportunities to learn how to do this, which likely led to limited understanding. Though she struggled with knowing how to introduce scientific language with her students, her attention to students' language use – as well as her focus on students' challenges and ideas – reflected her KCS. Even though KCS was less evident in science teaching, it is still important for informing science teaching practice – as Diana demonstrated.

Summary: Novice Elementary Teachers' CKT-S and Opportunities to Learn

The cases of the three novice elementary teachers demonstrate their strengths and limitations of their CKT-S and the variation in how they were supported to develop their CKT-S. The vignettes demonstrate how these novice elementary teachers drew on their CKT-S in their teaching practice – an understanding that has not extensively been investigated in the literature (e.g., Goodhew & Robertson, 2017; Johnson & Cotterman, 2015). Looking across the three cases we see three themes: (a) knowledge was most evident in practice when these teachers were provided support for developing that knowledge, (b) these teachers tended to draw on multiple aspects of their knowledge at the same time, and (c) some knowledge is more complex than other knowledge and may require more support to learn.

First, these novice elementary teachers tended to draw on their knowledge when provided adequate support for that knowledge. In particular, the teachers' knowledge of the science practices was not evident until they had opportunities to learn about the science practices in the Elementary Science Methods course. For example, Claudia and Harry drew on their KCT of the science practices more than their CCK of the science practices, which was also reflected in the opportunities to learn. Also, there was minimal evidence of the teachers' understanding of the

science practices before experiencing the opportunities to learn about them in the Elementary Science Methods course.

Second, these novice teachers drew on multiple aspects of their knowledge to support students' scientific sensemaking. For example, Claudia drew on her knowledge of how to engage students in scientific discussions and her knowledge of how to engage students in data analysis. Diana, similarly, drew on her knowledge of content and students and knowledge of content and teaching. Though it is not possible to determine from the data how the opportunities to learn foregrounded the use of knowledge sub-domains simultaneously, it does speak to the complexity of elementary science teaching. Knowing this complexity and the ways some novice elementary teachers draw on multiple sub-domains at the same time means more support may be needed for helping novices develop their understanding of how their knowledge in and for teaching is related.

Lastly, these novice teachers struggled with some sub-domains more than others and those they struggled with tended to also be minimally supported across the years. For example, knowing how to use scientific language with students and when to introduce scientific language was more challenging for these novice teachers, particularly when provided minimal opportunities to learn how to do this. More support may be needed since using scientific language is a prominent practice in elementary classrooms (Banilower et al., 2018). Also, as Harry demonstrated, knowledge of the applications of science was quite complex due to the need to understand the science concepts and practices, the students, and the social, political, and/or historical contexts in which the teacher is situated. It is not surprising, then, that some sub-domains were less evident in these teachers' practice, particularly when the teachers experienced fewer opportunities to learn. Overall, these teachers had similar opportunities to learn CKT-S yet

demonstrated subtle differences and many similarities in how they drew on that knowledge in their science teaching practice. Knowing how to teach elementary science is complex and requires quite a bit of support to do so. By knowing more about how some novice elementary teachers draw on their CKT-S over time and how some opportunities to learn can support their knowledge development, we can find ways to target our support of novice teachers' knowledge development to help them become well-started beginners.

The next chapter expands on the current findings by articulating what it means for novice elementary teachers to develop as well-started beginners and how practice-based teacher education and school contexts can support novice teachers in developing their knowledge in and for teaching science.

Chapter 7 Discussion and Implications

Many critical social issues require citizens to make informed science-related decisions based on their understanding of science and what they deem to be appropriate, accurate, and sufficient evidence. Learning to do this requires knowing about science concepts and how to evaluate and critique evidence to inform decision-making (National Research Council, 2012). Current science education reform refers to this learning as integrating three dimensions: disciplinary core ideas, crosscutting concepts, and science and engineering practices (National Research Council, 2012; NGSS Lead States, 2013).

Engaging students in three dimensional learning means teachers also need to understand the science concepts (disciplinary core ideas and crosscutting concepts) and the science and engineering practices. Yet, this can be challenging for elementary teachers, in particular, because they do not always have deep science knowledge (e.g., Abell, 2007) and they are required to know concepts and practices for many subjects (e.g., mathematics, language arts, history). Also, we know little about what elementary teachers know about the science practices (Davis et al., 2006). Much of what we know about elementary teachers' knowledge has been through methods external to their teaching practice (e.g., assessments, surveys), which gives insights into teachers' knowledge *for* teaching (Van Driel et al., 2014). However, what teachers know *for* teaching may not necessarily be evident *in* teaching practice (e.g., Zangori & Forbes, 2013). The current study extends the literature by also studying what three novice elementary teachers know *in* their teaching practice, as well as *for* their teaching practice. This chapter outlines how the current

study supports and extends the literature on teachers' knowledge and what it means to support teachers in developing their knowledge in and for teaching science.

In this chapter, I connect the current study to the literature on teachers' knowledge in and for teaching science. I then discuss what it means for novice elementary teachers to be "well-started beginners" and how the current study supports and extends this work through teachers' "science practice-readiness." Next, I discuss how the current study supports and extends the literature on opportunities to learn in teacher education and school contexts. In doing so, I discuss how one practice-based teacher education program supported knowledge development amidst a focus on teaching practice, as well as how the opportunities to learn within different contexts seemed to lead these teachers to seek other opportunities to learn supporting their knowledge development. In the last section, I outline the theoretical and methodological implications, as well as the practical implications for teacher educators, curriculum developers, and school personnel.

Elementary Teachers' Knowledge In and For Teaching Science Over Time

Knowledge in and for teaching science is the understanding that knowing how to teach is important both in an informative way (the "for" teaching; often evident in assessments and interviews) and in the moment-to-moment interactions that occur in the act of teaching (the "in" teaching; often evident in instruction and lesson planning). As Ball and Cohen (1999) comment, professional learning and knowledge about teaching should be situated "in and about the practices of teaching" (p. 13). Studying teachers' knowledge *for* teaching is important for knowing what teachers know about science teaching but does not necessarily mean they draw on that knowledge during their practice. Yet, much of the research on teachers' knowledge has been on knowledge *for* practice through the use of assessments, surveys, and so on (Van Driel et al.,

2014). That being said, only studying teachers' knowledge *in* practice still may not be enough to characterize what they know about teaching. For example, Zangori and Forbes (2013) found that elementary preservice teachers tended to have strong knowledge-*for*-practice about scientific explanations, but that same knowledge was not typically evident *in* their teaching practice. This demonstrates the need to study both knowledge *for* practice and knowledge *in* practice.

Though studying teachers' knowledge in and for teaching is important, few studies have done so (e.g., Goodhew & Robertson, 2017; Robertson et al., 2017). The few studies that have done so focused on how teachers' pedagogical content knowledge (PCK) is evident in teaching practice (e.g., Johnson & Cotterman, 2015; Park et al., 2011). In contrast, the content knowledge for teaching framework highlights the need to study all aspects of teachers' knowledge in their teaching practice (Ball et al., 2008), yet it has minimally been used in science education (for a few exceptions see Goodhew & Robertson, 2017; Johnson & Cotterman, 2015; Mikeska et al., 2018; Nixon et al., 2016; Nixon et al., 2019; Robertson et al., 2017). The few studies that have used it only studied teachers' knowledge of one or two sub-domains. The current study, however, extends the field by investigating many sub-domains of elementary teachers' CKT-S evident in their teaching practice. Also, longitudinal studies of teachers' knowledge are atypical in the current literature on teachers' knowledge (Schneider & Plasman, 2011). The current study extends the literature by not only studying the sub-domains of novice elementary teachers' CKT-S but does so across four years to characterize potential trajectories of elementary science teachers' knowledge development over time.

Strengths and Challenges with Studying CKT-S

Studying teachers' knowledge *in* practice means studying knowledge evident in their teaching practice. Knowledge *in* practice includes knowledge visible for anyone observing,

including students. For example, if a teacher demonstrates strong core content knowledge (CCK) of the science concepts on an assessment, that is helpful for the teacher and assessment evaluator. Yet that same teacher may or may not draw on that knowledge in their teaching practice (Zangori & Forbes, 2013). By not visibly drawing on that knowledge in their science teaching practice the knowledge therefore is not visible for students and could limit their opportunities to learn science. The novice elementary teachers in the current study regularly drew on their CCK of the science concepts and their CCK of the science practices after experiencing opportunities to learn about the science practices. By visibly drawing on those sub-domains in their teaching practice, they likely provided opportunities for their students to learn science.

A challenge with studying teachers' knowledge evident in their teaching practice is the limited visibility of some knowledge in practice compared with other knowledge. For example, for the novice elementary teachers in the current study, their knowledge of content and students (KCS) and their knowledge of content and curriculum (KCC) was evident in their lesson planning and reflections on their science teaching, but minimally evident in their instruction. Though not typically visible in instruction, these knowledge sub-domains may still inform instructional decision-making. For example, the work of teaching inherently involves working with and responding to students, which may mean knowing about students in science may be an "obvious" and therefore implicit understanding that teachers develop. Therefore, other methods may be necessary to identify teachers' implicit knowledge (e.g., assessments, surveys) (Schachter & Freeman, 2015; Zembal-Saul et al., 2000).

In comparison, other sub-domains (e.g., CCK of science concepts; CCK of science practices; KCT) are likely to be visible in many aspects of teaching practice (e.g., planning,

instruction, reflection) (Zangori & Forbes, 2013). If they are not visible, it may be limiting science learning opportunities for students (Park et al., 2011). Knowing which sub-domains of teachers' CKT-S are more visible in different aspects of teaching practice can inform the methods taken to study teacher knowledge in and for teaching science.

“Well-Started Beginners”: Potential Trajectories of Elementary Science Teachers

There are few studies that investigate the development of novice elementary science teachers over time (Mulholland & Wallace, 2005; Schneider & Plasman, 2011) and also few studies that investigate how opportunities to learn can support novices in developing their knowledge over time (Van Driel & Berry, 2017). The current study begins to fill this gap by not only studying three novice elementary teachers' knowledge development over time, but also by articulating similarities in these teachers' knowledge development and opportunities to learn across the four years – even though the teachers taught in different schools across the country. Though the current study only looked at three novice elementary teachers, it begins to provide insights as to the potential development of “well-started beginners” for elementary science teaching.

Being a “well-started beginner” for teaching science involves having a foundation for continued development of knowledge and practice over time. This foundation includes beginning strengths in knowledge and practices for teaching science. Avraamidou and Zembal-Saul (2010) argue that being a well-started beginner involves “supporting student learning through engagement in investigations and discussions about what [students] are learning” (p. 680). They argue that being a well-started beginner means moving beyond the typical trend of novice teachers who focus more on fun activities with minimal attention to scientific sensemaking (e.g., Gustafson & Rowell, 1995). Similarly, Hollon, Roth, and Anderson (1991) argue that being a

well-started beginner involves developing “a set of beliefs and conceptual tools that prepare [novice teachers] to reflect on and learn from [their] experience[s] as...teacher[s]” (p. 175). In both of these examples, being a well-started beginner is not about having extensive knowledge and practices for teaching, but instead it is about having a strong foundation of knowledge and teaching practice, as well as the know-how to continue developing throughout one’s career.

In the current study, the novice elementary teachers did not draw on their knowledge of all of the sub-domains of CKT-S throughout their teaching nor did they demonstrate strong knowledge of the dimensions of all of the science practices. Yet, all three novice elementary teachers regularly drew on their CCK of the science concepts. Similarly, once they had experiences learning about the science practices their knowledge of these became evident in their teaching practice. They also regularly drew on their knowledge of how to teach science. Contrary to the literature that argues that elementary teachers, particularly novice elementary teachers, have limited science knowledge (see Abell, 2007), these teachers represent cases of the possible for what knowledge well-started beginners may draw on in their science teaching practice.

Also, others have found that elementary teachers focus more on students’ enjoyment of science than to their learning about science concepts and practices (Furtak & Alonzo, 2010; Gustafson & Rowell, 1995). In comparison, the study of these novice elementary teachers found that by drawing on their knowledge of the science concepts and practices *in* their teaching practice (e.g., during instruction), they were engaging their students in lessons foregrounding science learning. Similar to other studies (e.g., Avraamidou & Zembal-Saul, 2010), these novice elementary teachers are examples of the possible for teaching elementary science that foregrounds scientific sensemaking.

Engaging students in scientific sensemaking involves engaging students in the science practices (Berland & Reiser, 2009; Bismack & Haefner, in press; Schwarz, Passmore, & Reiser, 2017). Doing so involves knowing about the science practices and how to engage students in them. Yet, the novice elementary teachers in this study demonstrated more limited understanding of the science practices (CCK about the science practices) and stronger knowledge of how to engage students in the science practices (knowledge of content and teaching [KCT] about the science practices). These teachers likely leveraged their stronger KCT about the science practices to meaningfully engage students in scientific sensemaking even while not understanding all dimensions of each science practice. This supports other work arguing that elementary teachers, in particular, may develop more extensive PCK before developing greater depth of their SMK (e.g., Davis & Petish, 2005). This also differs from studies with secondary teachers arguing that secondary teachers develop their SMK prior to developing their PCK (Van Driel et al., 1998). For elementary teaching, knowing how to teach about the science concepts and practices may provide a “foot in the door” for teaching elementary science with their SMK developing later in their career.

Science Practice-Readiness: Beginning knowledge about the science practices and how to teach them

Understanding the science practices and how to teach them is complex due to the detailed, interconnected nature of the science practices (Duschl & Bybee, 2014; National Research Council, 2012; Schwarz et al., 2017). Though the novice elementary teachers in this study understood how to teach about the science practices (KCT) more than the practices themselves (CCK: Science Practices), they understood particular dimensions within those sub-domains more than others. For example, within KCT of the science practices, these teachers

understood the need for students to be engaged in the science practices more than dimensions about supporting students' observation construction. Similarly, for CCK, these teachers understood claims, evidence, and reasoning (a heuristic for constructing explanations and arguments) (McNeill et al., 2006; Zembal-Saul et al., 2012) and the need to attend to errors in data more than understanding variables and controls in scientific investigations. The dimensions in which these novice elementary teachers demonstrated a stronger understanding may serve as a form of "readiness" for their understanding of and engagement in the science practices. These dimensions may serve as building blocks for these teachers' development of more sophisticated understandings later. Other teachers may demonstrate different strengths in understanding the dimensions of the science practices, which may serve as building blocks for further development for those teachers.

Drawing on the construct of reading-readiness (e.g., Farr & Anastasiow, 1969) and Smithey's (2008) notion of PCK-readiness, I developed the notion of "science practice-readiness." *Science practice-readiness* is a readiness to understand the science practices and how to engage students in the science practices. Smithey (2008) explained PCK readiness as a "collection of ideas" that become more connected over time as novice teachers develop their teaching practice (p. 27). Similarly, science practice-readiness is the notion that novice elementary teachers may develop initial understandings of the science practices and how to teach them that can serve as entry points into more developed understandings as they gain more teaching experience.

For KCT about the science practices, the novice teachers in this study demonstrated the strongest understanding that students should be the ones engaging in the science practices. This understanding may serve as a "foot in the door" for knowing how to engage students in the

science practices. Though this may seem like an obvious understanding, for novices it may not be as obvious. We know that novice teachers begin developing their practice through the “apprenticeship of observation” (Lortie, 1975), which in science, has tended not to prioritize students engaging in the science practices (Banilower et al., 2018; Banilower et al., 2013). We know from large-scale survey data that the instruction that the novice teachers received as students was more likely to involve teacher demonstrations or reading textbooks (Banilower et al., 2013). For this reason, understanding that students should be the ones doing the work of the science practices may be a novel understanding for these novice teachers and therefore part of their science practice-readiness. Once these novice teachers develop an understanding that students should be the ones engaging in the science practices, they may be able to build on this understanding to strengthen their knowledge of other dimensions of KCT of the science practices as they move beyond being well-started beginners.

For CCK about the science practices, these novice teachers mainly demonstrated the strongest understanding of the dimensions of science explanations and arguments. With the extensive supports in the Elementary Science Methods course through readings, course discussions, studying representations of practice, and rehearsals, this was not surprising. For the novice teachers in the current study, the dimensions of CCK about science explanations and arguments may serve as a foundation for future, more sophisticated understandings. Building on their understanding of those dimensions, as well as their understanding of the dimensions of KCT about the science practices, the novice teachers in the current study may later develop stronger understanding of other science practices as they experience other opportunities to learn and continue teaching. For example, understanding that science explanations and arguments need to be supported by evidence may be a foundation for further understanding about what

constitutes appropriate and sufficient evidence (e.g., accurate and objective observations serve as evidence). Yet, supporting novice elementary teachers to develop science practice-readiness that can serve as foundational knowledge for further understanding about the science practices and how to teach them requires extensive and varied opportunities to learn.

The novice elementary teachers in the current study took a science methods course that foregrounded science explanations and arguments and how to engage students in the science practices, particularly by having students doing the intellectual work. Not surprisingly, those dimensions became the foundation of science practice-readiness for these novice elementary teachers. This supports other studies about the extent of support novices need to understand the science practices (CCK about the science practices) and how to engage students in the science practices (KCT about the science practices) (e.g., Grossman, Compton, et al., 2009; Hollon et al., 1991; Windschitl et al., 2008; Zembal-Saul, 2009). Science teacher educators, therefore, need to consider what foundational knowledge they want their preservice elementary teachers to develop with the goal that the dimensions will likely develop more coherence and depth as the teachers gain more teaching experience. Also, science teacher educators should recognize that novice elementary teachers are not likely to develop a strong understanding of *all* dimensions of CCK and KCT of *all* of the science practices. In particular, the focus is on developing novice teachers' science practice-readiness that could serve as "conceptual tools" for further "learn[ing] from [their] experience[s] as... teacher[s]" (Hollon et al., 1991, p. 175). The novice teachers in the current study provide examples for how "well-started beginners" can make sense of their knowledge in their science teaching practice and what science practice-readiness might look like for well-started beginning teachers. They serve as further existence proofs of the possibilities for novice elementary teachers (Avraamidou & Zembal-Saul, 2010; Hollon et al., 1991).

Opportunities to Learn CKT-S Across Contexts

Now that we know it is possible for novice teachers to develop the foundation of their CKT-S for being well-started beginners, the question still remains, *What opportunities support novice elementary teachers' development of their CKT-S in order to become well-started beginners?* Few studies investigate opportunities in both teacher education programs and school teaching experiences and those that do tend to investigate how the opportunities support teaching practice (Darling-Hammond, 2006a, 2006b; McDonald et al., 2011) and not teachers' knowledge (Van Driel & Berry, 2017). The current study extends the field by investigating the opportunities across a practice-based teacher education program and school contexts for supporting novice elementary teachers' knowledge development.

One way the practice-based teacher education program in the current study supported the novice elementary teachers' knowledge development was by providing opportunities supporting the teachers' CCK of the science practices. Similar to other studies investigating the influences of science methods courses on teachers' knowledge development (Van Driel & Berry, 2017), the Elementary Science Methods course provided the main opportunities to learn about the science practices.

Another way the practice-based teacher education program and the teaching experiences supported these novice teachers' knowledge development was by providing opportunities to learn that supported their PCK. For example, similar to other studies (Van Driel et al., 2002), the novice teachers in the current study identified the teaching experiences as supporting their understanding of students' strengths and challenges with science concepts (KCS), as well as how to teach science (KCT) (Loughran, 2014; Van Driel et al., 2002). The Children as Sensemakers course also provided opportunities supporting these teachers' KCS and KCT. Also, there were

some opportunities in the Teaching with Curriculum Materials course that supported these teachers' KCC.

Within the coursework foregrounding science teaching in this teacher education program and these teachers' interviews and surveys, there were few opportunities to learn that supported their CCK of the science concepts, horizon content knowledge, knowledge of the connection of science to non-science disciplines, and knowledge of the applications of science. The current study only investigated the opportunities to learn through the teachers' second year teaching. Perhaps later in these teachers' careers they may experience opportunities to develop their CCK of the science concepts (Arzi & White, 2008; Mulholland & Wallace, 2005). Also, investigation of other sources for opportunities to learn (e.g., curriculum materials; science content coursework prior to the teacher education program) may provide further insights into opportunities supporting their CKT-S (Arzi & White, 2008; Haefner & Zembal-Saul, 2004). Further work is needed to determine how other opportunities to learn could support teachers' development of those sub-domains.

Practice-Based Teacher Education: Supporting Practice and Knowledge Development

Many novice elementary teachers experience their main opportunities to develop PCK during their teacher education programs. In particular, practice-based teacher education programs focus on supporting novices to do the work of teaching, which is both unnatural and challenging (Ball & Forzani, 2009). It involves decomposing teaching into more manageable aspects and then engaging novices in the study of representations of those decomposed aspects of teaching (Grossman, Compton, et al., 2009). It also involves rehearsing the decomposed aspects and working to "put them back together" to inform teaching practice (Grossman, Compton, et al., 2009; Lampert et al., 2013).

Rehearsing decomposed aspects of science teaching requires modeling and guided practice (Hollon et al., 1991). This occurred in the practice-based teacher education program in the current study in various ways. For example, in the Children as Sensemakers course, the novice teachers interviewed a young child about their science ideas. When doing so, they focused on practicing how to elicit students' ideas about day and night and sound. They were given prompts to ask the child, such as "Please tell me how you think we have day and night?" and "Can you tell me more about...?" (Y1 CaSM Initial Interview Protocol). This type of practice was a way for the novice teachers to engage in the study of a less complex part of teaching (eliciting students' thinking) in a supportive, guided way.

Yet, developing teaching practice also involves developing the knowledge in and for teaching. Ball and Forzani (2009) articulated this when they said that "a practice-focused curriculum for learning teaching would include significant attention not just to the knowledge demands of teaching but to the actual tasks and activities involved in the work" (p. 503). As they discussed, the shift in practice-based teacher education is to orient the work of learning to teach on the practice of teaching.

The current study expands the characterization of practice-based teacher education to emphasize how opportunities that support teaching practice can also support knowledge development (Korthagen, Loughran, & Russell, 2006). For example, the rehearsals (Lampert, 2010) in the Elementary Science Methods course intended to support novice teachers' science teaching practices (Davis, in press). At the same time, the current study found that they also provided opportunities for the novice teachers to develop their CKT-S. This occurred for Claudia when she led a discussion about a representation of temperature data during a science teaching rehearsal in the Elementary Science Methods course. She drew on her knowledge of

representations as including class data (CCK of analyzing and interpreting data), as well as her understanding of how to support students in constructing their own representations of the data (KCT of analyzing and interpreting data). Throughout this practice-based teacher education program, the experiences that were designed to support these novice elementary teachers' science teaching practices also served as opportunities to develop their CKT-S. The current study thereby supports the literature on how practice-based teacher education programs can focus on practice while also supporting teachers' knowledge development (Davis & Boerst, 2014) – both integral to supporting the development of well-started beginner.

Interactions of Opportunities to Learn

The few studies that have investigated teachers' knowledge development have minimally considered the interactions of the opportunities to learn (Van Driel & Berry, 2017). In the current study, I found that opportunities supporting the sub-domains of PCK led these novice teachers to seek out opportunities to develop their understanding of the science concepts. As these novice teachers interacted with standards, curriculum materials, and students during their planning and instruction, they were confronted with gaps in their CCK of the science concepts. These teachers discussed pursuing other opportunities to fill those gaps in their CCK of the science concepts. In this way, the opportunities that supported these teachers' knowledge of the sub-domains of PCK led to opportunities to develop their CCK of the science concepts. These teachers also discussed how their opportunities to make sense of science concepts supported the opportunities to understand standards (part of their PCK). In this way, a cyclical interaction developed between the opportunities supporting these teachers' PCK and their CCK of the science concepts (see Figure 7-1). This was only apparent, however, for opportunities supporting these teachers' CCK of the science concepts and not the science practices.

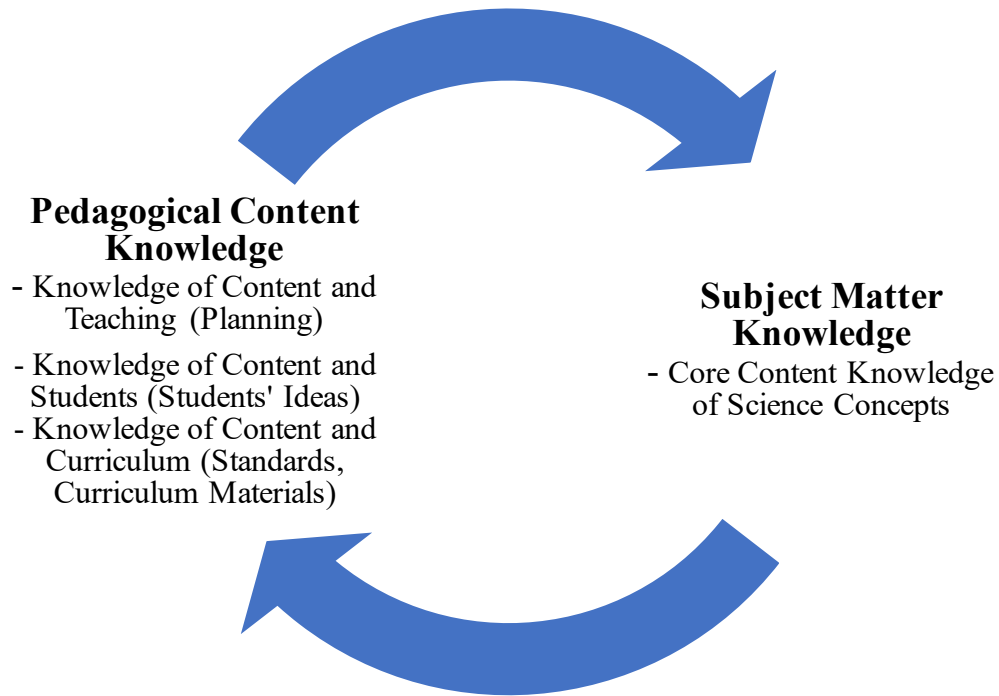


Figure 7-1. Cyclical interaction of opportunities supporting these novice elementary teachers' SMK and PCK

The interaction between the opportunities in the current study to develop PCK and CCK of the science concepts demonstrates a synergy of opportunities to learn. In particular, this study suggests that developing an understanding of science concepts may not always be a precursor to developing PCK – as is typically characterized in the literature (Loughran, 2014; Van Driel et al., 1998). Instead, for elementary teachers their potentially limited depth of knowledge of science concepts may mean they “don’t know what they don’t know.” Therefore, engaging in opportunities supporting their PCK could provide insights about their potentially limited SMK and thereby lead them to pursue further opportunities to learn science. This is also supported, for example, by these novice elementary teachers’ stronger KCT of the science practices than their

knowledge of the practices themselves (CCK of the science practices). Elementary teachers' potential development of their PCK prior to or congruent with their SMK supports some studies (e.g., Davis & Petish, 2005) and contrasts with others arguing that teachers should develop their SMK prior to their PCK (Van Driel et al., 1998). More work is needed to determine whether this interaction of opportunities to learn PCK and SMK is typical for other elementary science teachers, but this study suggests that learning how to teach science may help some teachers identify what they do not know about the science concepts and therefore may lead them to pursue further opportunities to develop deeper knowledge about science.

Implications

Supporting novice elementary teachers in becoming well-started beginners involves consideration of how teacher education programs and school contexts can support the teachers over time. Yet, knowing how to support novice elementary teachers involves knowing how the novice teachers develop their CKT-S over time. To inform further research, my dissertation study includes theoretical implications for how three novice teachers developed their CKT-S over time and methodological implications for further longitudinal studies of novice elementary teachers' knowledge development. To inform supports for novice teachers, my dissertation study also provides practical implications for teacher educators, curriculum developers, and school personnel in how they can potentially support novice teachers as they begin their careers and work to develop into well-started beginners and later into master teachers.

Theoretical Implications

My dissertation study has theoretical implications for novice elementary teachers' trajectories of CKT-S in their teacher education programs and continuing into their first two years of teaching. Similarly, there are implications for how opportunities to learn can support

novices as they develop over time. Based on the novice elementary teachers in the current study, Figure 7-2 represents a possible trajectory of novice elementary teachers' visible CKT-S and how opportunities to learn in a practice-based teacher education program and school contexts might support novice teachers' knowledge development over time. The figure is based on the commonalities across the three participants in this study and is not intended to generalize to all teachers, as I explicate below.

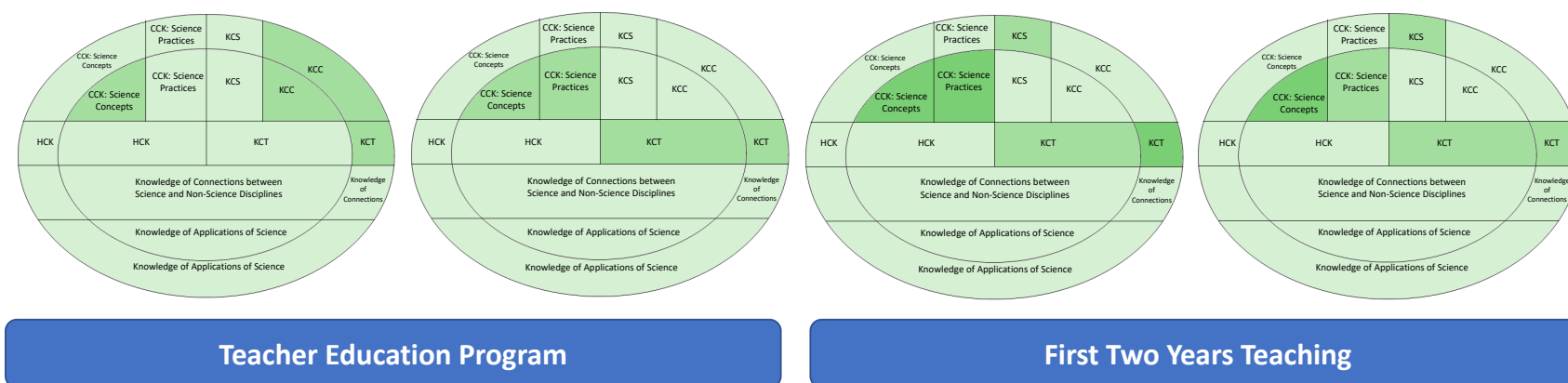


Figure 7-2. Potential Trajectory of Novice Elementary Teachers' CKT-S Over Time and Opportunities to Learn within a Practice-Based Teacher Education Program and the First Two Years Teaching

As represented in Figure 7-2, throughout the four years, these well-started novice elementary teachers demonstrated some CCK of the science concepts. They participated in a science methods course that foregrounded the science practices and began drawing on their CCK of the science practices once they learned about the science practices. Similarly, once the novice elementary teachers participated in a science methods course designed to support their understanding of how to teach science, they began to draw on that knowledge more extensively in their teaching practice (KCT). This seemed to continue as these novice elementary teachers moved into their first two years of teaching. Also, the novice teachers' KCS and KCC may be implicit knowledge that informed their teaching practice but was not necessarily visible in their instruction. Other novice elementary teachers might demonstrate a similar trajectory, particularly if they experience a similar set of opportunities to learn.

As for the other sub-domains, there may be minimal evidence of such knowledge in teachers' science teaching practices unless they are provided extensive support for understanding those sub-domains. The first two years of teaching may provide some support for helping novice teachers develop their KCT, KCS, and KCC with minimal to no support for developing other sub-domains of their CKT-S, depending on the school contexts. The teachers in this study were not provided much support for developing their horizon content knowledge, knowledge of the connections of science to non-science disciplines, and knowledge of the applications of science, and they did not demonstrate this knowledge in their teaching practice. Other teachers, too, might need more support for developing or demonstrating these knowledge sub-domains. Further research is needed of trajectories for other novice elementary teachers for how they draw on their knowledge in their teaching practice. For example, studying other novice elementary teachers in different contexts with different learning opportunities could expand our understanding of how

opportunities to learn support knowledge development and how well-started beginners draw on their knowledge in their teaching practice. Also, extending studies through the first few years of teaching and beyond will give insights into how novice teachers' knowledge develops from well-started beginners into more experienced, master teachers. Being able to develop and compare different trajectories of elementary teachers' knowledge development over time will allow for further insights of how to support novices in becoming well-started beginners.

Currently, few longitudinal studies exist on how elementary teachers develop their knowledge over time (Mulholland & Wallace, 2005; Schneider & Plasman, 2011). In particular, there has been minimal research on how the content knowledge for teaching framework, originally developed in mathematics (Ball et al., 2008), is useful for studying science teachers' knowledge in and for teaching science (Johnson & Cotterman, 2015; Nixon et al., 2019; Robertson et al., 2017) with even fewer studies investigating elementary teachers' CKT-S (Mikeska et al., 2018; Mikeska et al., 2017). Also, the addition of two other sub-domains means further work is needed to consider the applicability of this framework in science education.

The two new sub-domains –knowledge of the connection of science to non-science disciplines and knowledge of the applications of science – were both minimally evident in the novice elementary teachers' teaching practice and were minimally supported across the four years. However, the minimal evidence and support does not mean the sub-domains are unnecessary or that they should not be included in the framework, but that more work is needed as to how teachers make sense of them and use them. By comparing the literature on these two knowledge sub-domains and how the teachers in the current study made sense of them in the few instances when they were evident, we can gain some insights for further research.

Knowledge of the Connection of Science to Non-Science Disciplines. Teachers' knowledge of the connection of science to non-science disciplines was developed from Shulman's (1986) lateral curricular knowledge. He argued that this knowledge was "the teacher's ability to relate the content of a given course or lesson to topics or issues being discussed simultaneously in other classes" (p. 10). In the few instances when this knowledge was evident in the teachers' science teaching practices in the current study, they tended to demonstrate it as Shulman articulated it – as connecting with a concept in another discipline. For example, Diana said, "okay, let's look at graphing. We are actually going to be learning this in math, this week" (Y3 Diana Video 1). As this quote demonstrates, Diana understood that constructing and using graphs is part of science and mathematics curriculum (KCC [for science] – a sub-domain of PCK). She also understood that using graphs to represent data is important in both disciplines (CCK of the science practices – a sub-domain of SMK). Yet, the depth of Diana's understanding of the relationship of this concept in both disciplines is unclear.

Shulman (1986) situated this knowledge sub-domain under teachers' PCK. It may still be that this sub-domain is only situated under PCK, but the limited data from the current study does not provide insights into clarifying these questions. Further work is needed to understand how other teachers understand the relationships between concepts and practices that span multiple disciplines to determine if their understanding only connects with their understanding of the curricula (part of PCK) or if there is greater depth of CCK (part of SMK) needed to understand the connections of science to non-science disciplines.

Knowledge of the Applications of Science. Teachers' knowledge of the application of science is a sub-domain that has not previously been identified in the literature on science teacher knowledge. In comparison, it has been identified in the literature on science teaching

practices as critical for teaching science (e.g., Davis & Petish, 2005; Kloser, 2014). Within this literature, teachers' practice of connecting science to its applications is described as,

Teacher engaging students in discussions or activities that integrate the significance of scientific accounts and practices in students' daily lives and the world around them, including connections to science in current events, the historical context of science, and STS issues (Kloser, 2014, p. 1203).

As this description implies, teachers engaging in this practice need an understanding of their students' lived experiences (KCS), but also depth in understanding science and its many dimensions (e.g., historical context of science, science in current events). This second part of understanding is related to teachers' CCK of science concepts and practices, as well as how the concepts and practices relate to social, political, and historical issues in the local community and beyond.

In the current study, the minimal evidence of the teachers' knowledge of the applications of science does not provide robust insights for clarifying the complexity of this knowledge sub-domain. In the few instances when the knowledge was evident, it connected to students' lived experiences and typically not to broader social, political, and historical contexts. This was similar for the few opportunities to learn that supported the teachers' knowledge of the applications of science. In a sense, the opportunities and the evidence in their teaching practice occurred on a more superficial level.

For novice elementary teachers, it may be that developing knowledge of the applications of science is more complex than can be developed in a practice-based teacher education program and the first few years of teaching. The complexity of understanding the many dimensions of the applications of science (e.g., science concepts and practices, students' experiences, the social,

political, and historical contexts of science) may take longer to develop. Also, unlike other sub-domains of CKT-S, knowledge of the applications of science seems to relate to more sub-domains and contexts. For example, it involves knowing more than just students' challenges in science or the science concepts. It also involves knowing about the social, political, and historical issues, among others, that relate to the discipline and how people make sense of it. Further work is needed to determine how teachers – possibly more experienced teachers – make sense of their knowledge of the applications of science and how this can be more supported for novices and experienced teachers alike.

Summary: Theoretical Implications. Due to the limited use of this framework in science education, more research is needed to investigate its usefulness and further unpack the sub-domains. In particular, unpacking what it means for elementary science teachers to have knowledge in and for practice related to sub-domains that were minimally evident in their practice (KCS, KCC, HCK, knowledge of the connections of science to non-science disciplines, knowledge of the applications of science). Also, further study is needed of teachers' specialized content knowledge, which was not investigated in the current study due to the subtle nature of that sub-domain (Ball & Bass, 2000, 2003; Johnson & Cotterman, 2015; Thames, 2008). Comparisons should also be studied between experienced teachers' knowledge and novice elementary teachers' knowledge to provide insights into how well-started beginners develop into master teachers. Some potential questions for further research include:

- *Why were some sub-domains minimally evident in teaching practice compared to others?*
- *Do more experienced elementary teachers demonstrate their CKT-S in similar ways as novice elementary teachers and how?*

- *What does it mean for teachers to have and draw on their knowledge of the connection of science to non-science disciplines?*
- *What does it mean for teachers to have and draw on their knowledge of the applications of science?*

Lastly, as the CKT-S framework is investigated more in science, it should be compared to other frameworks of teacher knowledge (e.g., Teacher Pedagogical Knowledge & Skill (Gess-Newsome, 2015)) to determine the strengths, weaknesses, and applicability of each framework in different contexts and with different teachers.

Methodological Implications

This dissertation also has methodological implications for conducting longitudinal studies of elementary teachers' CKT-S and the opportunities to learn over time. There are affordances and constraints for using different methods to study novice elementary teachers' CKT-S over time and the concurrent opportunities to learn.

Studying elementary teachers' CKT-S. Even though there have been calls for more studies investigating teachers' knowledge development over time (Avraamidou & Zembal-Saul, 2010; Schneider & Plasman, 2011), few studies have taken up this call (Arzi & White, 2008; Avraamidou & Zembal-Saul, 2010; Mulholland & Wallace, 2005). An affordance for doing so is to see how teachers' knowledge develops and changes over time. However, conducting longitudinal research on teachers' knowledge development is challenging. For example, most longitudinal studies have small numbers of participants (see Arias & Davis, 2017a; Arzi & White, 2008; Avraamidou & Zembal-Saul, 2010; Mulholland & Wallace, 2005). The current study is no exception with only three participants. Following participants for extended periods of time is challenging. It is time consuming and resource demanding, while also logistically

challenging because of teachers' movement throughout their careers (e.g., Borman & Dowling, 2008). Yet, more longitudinal research on teachers' knowledge development is needed to see how they develop from well-started beginners to experienced, master teachers, which can take at least 5 to 7 years (Feiman-Nemser, 2001).

When studying teachers' CKT-S, it is important to not only study knowledge development over time, but to also gather a variety of data sources. Because some knowledge sub-domains may be more evident in certain aspects of science teaching practice compared to others (e.g., KCS was more evident for these novice teachers in lesson planning and reflections than instruction), using more data sources will allow researchers to "see" the knowledge in practice in different ways. For example, using a combination of assessments, surveys, videos of instruction, lesson plan artifacts, and interviews may provide more insights into the knowledge teachers "have" and how they draw on that knowledge in their teaching practice, than using only some of those data sources (Zangori & Forbes, 2013).

Studying opportunities to learn across contexts. There have been many studies of resources and foci of teacher education programs with most studies investigating teacher outcomes (e.g., Darling-Hammond, 2006a; Darling-Hammond, 2006b), as well as a few studies investigating opportunities within school contexts (Appleton & Kindt, 2002; Larkin et al., 2009). The many studies that have investigated teacher education programs tend to use syllabi as the main way to determine opportunities to learn in programs (e.g., Rickenbrode et al., 2018). Yet, as the current study demonstrated, using only syllabi is inadequate to represent the many opportunities to learn across teacher education programs. Similar to studying teachers' knowledge, multiple types of data sources are necessary for studying how teacher education programs and school contexts support novice teachers' knowledge development. In the current

study, for example, the opportunities to learn in the teacher education program spanned course syllabi, assignments, readings, slides, and class sessions (as evident in videorecords of class sessions in the Elementary Science Methods course). Also, in order to gain insights into the ways novice teachers are supported in becoming well-started beginners, opportunities to learn should be investigated in depth in both what opportunities are provided, as well as how the opportunities relate to one another.

Lastly, most studies investigating opportunities to learn focus on how the opportunities support teaching practice with few investigating how opportunities to learn support knowledge development (Van Driel & Berry, 2017). The few studies that do investigate how opportunities to learn support knowledge development do so within a single course or multiple courses in a teacher education program (Van Driel & Berry, 2017). Similarly, the few studies that investigate opportunities to learn in school contexts do so in one or two schools and rarely consider opportunities to learn across teacher education programs and school contexts (Appleton & Kindt, 2002). Longitudinal studies of greater length and depth should be undertaken to gain further insight into what and how opportunities in teacher education programs and school contexts can support novice teachers' knowledge development.

Implications for Teacher Educators, Curriculum Developers, School Personnel, and Institutions

This dissertation has implications for teacher educators, curriculum developers, and school personnel for considering ways to support novice elementary teachers in developing their CKT-S over time. In particular, the implications for teacher educators considers how they can provide opportunities to learn that will support novice elementary teachers in becoming well-started beginners. Also, implications for curriculum developers, school personnel, and

institutions include providing opportunities to learn that support novice elementary teachers in developing their CKT-S during their first few years of teaching, as well as helping them develop from well-started beginners into master teachers further into their careers.

Implications for Teacher Educators. Teacher education programs typically provide the first formal education for novice teachers to develop their knowledge and practices for becoming well-started beginning teachers. Teacher educators need to consider what it means to develop well-started beginners and target their teaching toward the foundational knowledge and practices in and for teaching (Davis & Boerst, 2014). Doing so may require teacher educators to identify the necessary opportunities to learn that foreground teachers' PCK and CCK of the science practices, because these may be the main knowledge sub-domains supported in teacher education programs. Yet, as the current study found, assuming novice elementary teachers can develop all aspects of their PCK and CCK of the science practices is unrealistic. Instead, teacher educators could determine what will be the foundation for novices to develop as well-started beginners whose knowledge will continue to deepen as they develop their teaching practice throughout their careers (Davis & Boerst, 2014; Mikeska, Anderson, & Schwarz, 2009).

Novice teachers' initial understandings of PCK serve as a form of PCK-readiness that will become more connected over time (Davis & Smithey, 2009; Smithey, 2008). Similarly, novice elementary teachers may also develop a type of science practice-readiness for understanding the science practices and how to engage students in them. Hammerness, Darling-Hammond, Grossman, Rust, and Shulman (2005) argue that readiness should "guide decisions about where to start and how to scaffold learning so that [novice elementary teachers] are enabled to develop critical skills and abilities" (p. 400). This means teacher educators could consider what aspects of science-practice readiness they intend to support in their coursework. It

may be too much for novices to develop deep, connected knowledge of all of the science practices and how to teach them so teacher educators should prioritize a few science practices to focus on (Windschitl et al., 2008).

For example, for some novice teachers, understanding the parts of a heuristic for scientific explanations and arguments (claim, evidence, and reasoning) could serve as the science practice-readiness to begin making sense of those science practices in greater depth over time. Similarly, understanding that students should be the ones engaging in the science practices could serve as a form of science practice-readiness for knowing how to engage students in the science practices. The dimensions that serve as science practice-readiness for every novice elementary teacher will likely vary depending on the opportunities to learn provided in teacher education programs, as well as the teachers' own experiences and identities.

Lastly, developing as well-started beginners means knowing how to continue to develop one's knowledge and teaching practice over time. For teacher educators, this may mean being explicit for novice teachers about when they should seek out other opportunities to learn. In the current study, the novice teachers sought other opportunities to develop their CCK of science concepts when engaging in opportunities to develop their PCK (e.g., reading standards, curriculum materials, or eliciting students' ideas). To help other novice teachers learn how and when to pursue other opportunities to learn, teacher educators could make this explicit for the novices. In particular, they could discuss what it means to seek other opportunities to learn, where to find other opportunities, and how to recognize when they should seek other opportunities. Part of being a well-started beginner involves having the foundational knowledge and practices for teaching, as well as the know-how to continue developing as a professional.

Implications for curriculum developers. In the school contexts, the main science-related opportunities to learn for the teachers in the current study occurred from their teaching experiences. This is not to say that other opportunities to learn did not exist or influence their science teaching, but that their teaching experiences played a prominent role in supporting their development of their CKT-S. For example, when available, these teachers read the curriculum materials, which supported their day-to-day science teaching practices. Further studies of how curriculum materials, particularly educative curriculum materials, can support teachers' knowledge development are needed to help novice teachers move beyond being well-started beginners (e.g., Arias, Bismack, et al., 2016; Bismack et al., 2015; Schneider & Krajcik, 2002). One way may be for studies of educative curriculum materials to investigate how they can support novice teachers to develop more connected knowledge of the science practices that build from novice teachers' science practice-readiness (Arias, Davis, Marino, Kademian, & Palincsar, 2016).

Along with the curriculum materials, other school and classroom resources tended to influence these novice elementary teachers' science teaching. Similar to other studies (Appleton, 2003; Appleton & Kindt, 2002; Bismack et al., 2014; Marx & Harris, 2006), physical materials and time, for example, were both mentioned by these novice elementary teachers as influencing their science teaching. The continued strain of the focus on language arts and mathematics in elementary classrooms will not alleviate the concern about the lack of time for teaching science (Banilower et al., 2018; Marx & Harris, 2006). Possibly finding ways to help novice elementary teachers develop their knowledge of the connection of science to non-science disciplines may be one way to help them see more connections between science and language arts and mathematics.

Doing so may lead to increased teaching of science in elementary classrooms. Providing this type of support can come from curriculum developers, administrators, or even colleagues.

Implications for school personnel. Continued and more extensive support from colleagues will be important for helping novice elementary teachers develop beyond being well-started beginners. For example, both Claudia and Harry mentioned having time to plan with their colleagues, but that their colleagues did not teach science to the same extent – or in the same investigation-based way – that they taught science. Claudia described this when she said,

[For] my two other colleagues, science is the first thing to go. And I did a whole two weeks of all these lessons that you saw, and so that we could then talk about decomposition and build these ecosystems. And they just skipped all that and built the decomposition systems (Y3 Claudia Interview 3).

Claudia's comments demonstrate how she viewed her way of teaching science, aimed at supporting students' sensemaking, as different from how her colleagues taught science. Though she appreciated having time to co-plan with her colleagues, the co-planning and other interactions did not involve "collaborative investigation of important problems of practice" (Hollon et al., 1991, p. 177), according to Claudia, which would have allowed for further development of her science teaching practice. Providing novice elementary teachers with supportive communities of practice, for example, may be ways to help them develop greater depth of CKT-S and transition from novice elementary teachers to master teachers (Loughran, 2014).

Implications for institutional change. Though these novice elementary teachers were well-started beginners they still struggled with the overwhelming nature of teaching. Hollon and colleagues (1991) discussed the need "to restructure the institutional demands of teaching in

ways that make the curricular and instructional tasks possible to accomplish in typical classroom and school environments” (p. 179). Even though these novice teachers taught over two decades after Hollon and colleagues called for institutional change to make science teaching more feasible, these novice teachers still experienced the strain of elementary teaching. For example, during an interview Diana discussed the many other expectations placed on her beyond teaching the curriculum. She said,

I don’t know how we’re going to get things done these next couple weeks. It’s just insane... because [the students] have two weeks before spring break. We have three field trips...And we’re supposed to be benchmarking. And we’re supposed to be doing guided reading groups at the same time. And right when we get back from break, it’s testing (Y4 Diana Interview 1).

In this quote, Diana notes the many expectations placed on her as an elementary teacher, none of which related to science teaching. Even though these novice elementary teachers demonstrated knowledge consistent with being well-started beginners, they still faced the struggles of novice teachers when maneuvering the “institutional demands of teaching” (Hollon et al., 1991). The strains placed on elementary teachers and lack of accountability for science teaching will only decrease the quality and quantity of science teaching over time. If we truly expect students to meet the high expectations outlined in the NGSS, then institutional changes need to be made to mediate the extensive – often non-science – expectations placed on elementary teachers.

Limitations and Next Steps

This dissertation study investigated how three novice elementary teachers developed their CKT-S within a practice-based teacher education program and their first two years of teaching. I also investigated how the opportunities to learn within the practice-based teacher education

program and school contexts provided support for the teachers' CKT-S. By articulating what it means for novice elementary teachers to develop their knowledge as well-started beginners, this study includes implications for teacher educators, curriculum developers, school personnel, and institutions for how to provide continual support for such knowledge development. However, the focus on only three novice elementary teachers limits the generalizability of the findings. Instead, similar to other studies (e.g., Avraamidou & Zembal-Saul, 2010; Bismack & Haefner, in press), the findings from the current study outline the image of the possible for the development of well-started beginning elementary science teachers and how to support their knowledge development.

Also, the practice-based teacher education program for which the novice elementary teachers participated may not be representative of other teacher education programs throughout the country or world. The current study does provide insights into how one practice-based teacher education program was able to provide opportunities to learn that support novice elementary teachers' development of their CKT-S – insights that are only speculative in the literature (Roth, 2014). Further research is needed with other practice-based teacher education programs to provide insights into how they support knowledge development among their elementary science teachers. Also, studies should compare the practice-based teacher education programs with general teacher education programs to determine similarities and differences among opportunities to learn and what that means for the development of well-started beginning elementary science teachers.

A further limitation of the study of teachers' CKT-S in their teaching practice is the inability to “see” all aspects of their knowledge. For example, the novice elementary teachers' KCS and KCC was mainly evident in their lesson planning and reflections on their science

teaching and only moderately evident at that. Though I used data sources that are records of teaching practice, they only include what the teachers wrote or said, not what was “in their heads.” For this reason, I am not able to make claims about what knowledge the teachers “have,” but instead what knowledge is “evident” in their teaching practice. Comparing what knowledge teachers “have” to what knowledge is “evident” in their teaching practice will require even more comprehensive data sources and analyses (for examples of how to do this, see Park et al., 2011; Zangori & Forbes, 2013).

Lastly, I used a variety of data sources to study the opportunities to learn that the novice elementary teachers had for supporting their development of their CKT-S. Yet, when the teachers entered their first two years of teaching, I was not able to capture all of the different experiences and resources available to them that may provide opportunities to develop their CKT-S. For example, I did not gather data from the few professional development experiences that Claudia and Harry had, nor did I analyze the curriculum materials for opportunities to learn. Both of those sources have been found to support teachers’ knowledge development in varying ways (e.g., Roth et al., 2011; Schneider & Krajcik, 2002). By not including those data sources, among others, when studying the opportunities to learn, I limited my ability to make claims about all opportunities to learn available to the novice elementary teachers. Further research is needed that includes even more extensive sources, particularly in the school contexts, to investigate how all opportunities to learn can support novice elementary teachers’ development of their CKT-S.

Conclusion

Current science education reform documents call for science teaching that integrates science practices with science concepts in order for students to develop the necessary knowledge

and skills to become scientifically literate citizens. However, teaching science in this reform-oriented way is complicated and atypical in elementary classrooms, though not impossible. As the current study demonstrates, novice elementary teachers have the potential to develop their knowledge in and for teaching science when provided the necessary opportunities to learn.

Practice-based teacher education programs are one way to provide opportunities that support the knowledge and practices for teaching elementary science. When novice teachers move into their first few years of teaching, they continue to experience some opportunities to learn that support their PCK, but not necessarily other sub-domains. Further work is needed on how to provide more opportunities to learn that support novice elementary teachers' continued development of their understanding of science concepts and practices, as well as how to apply those concepts and practices to social, political, and historical issues beyond the classroom, among other sub-domains. Teaching elementary science is complex but developing the necessary knowledge in and for teaching science can help teachers know how to support students in becoming informed citizens able to make decisions about science-related social issues.

Appendices

Appendix A: Instructional Planning Template

ED421 Elementary Science Methods

INSTRUCTIONAL PLANNING TEMPLATE

for planning science lessons

Please complete this version of the template. However, please also see the guidance provided in the "annotated version" of this document, found starting on page 4 of this file. This will help you develop a high-quality science lesson plan oriented to the EEE framework.

Overview and Context

Your name(s):	
Grade level and school:	
Title of lesson/activity:	
Teaching date(s) and time(s):	
Estimated time for lesson/activity:	
Overview of lesson:	
Context of lesson:	
Sources:	

Learning Goals and Assessments

Learning Goals (1-2 in each)	Connection to Standards (Michigan GLCEs and/or Next Generation Science Standards)	Type of Assessment	Connection to Activities
SCIENCE CONTENT / DISCIPLINARY CORE IDEAS Students will be able to...			
SCIENTIFIC PRACTICES Students will be able to...			
IF APPLICABLE: CROSSCUTTING CONCEPTS Students will be able to...			

IF PREFERRED: You may integrate your learning goal statement (disciplinary core idea x scientific practice x crosscutting concept)			
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EEE Connection	
Investigation question students will answer:	
Claim with evidence and reasoning you hope students will generate:	I think _____ (claim). I think this because I've seen or done _____ (evidence). <i>as appropriate [see annotation below]:</i> The science idea or principle that helps me explain this is _____ (reasoning). This helps me use my evidence to support my claim because _____.

Attending to the Learners

Anticipating student ideas, including alternative ideas, misconceptions, and prior knowledge:	
Making the content accessible to all students, including using specific leverage points for promoting equitable science instruction from class:	

Instructional Sequence

Materials:	
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Instructional Sequence: Engage Element

	Steps for Engage Element
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Time	The teacher will: •	The students will: •
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Management Considerations for Engage Element:

Instructional Sequence: Experience Element

	Steps for Experience Element	
Time	The teacher will: •	The students will: •

Management Considerations for Experience Element:

Instructional Sequence: Explain Element

	Steps for Explain Element	
Time	The teacher will: •	The students will: •

Management Considerations for Explain Element:

Reflection on Planning

Learning goal for self:	
Preparing to teach this lesson:	

ED421 Elementary Science Methods
INSTRUCTIONAL PLANNING TEMPLATE (Annotated)
for planning science lessons

Overview and Context

Section	Description	Main Connection to Instructional Planning Considerations
Your name(s):	Indicate your name(s).	
Grade level and school:	Indicate the grade level of the students and the school site for the lesson.	
Title of lesson/activity:	Indicate the title of the lesson/activity.	
Teaching date(s) and time(s):	Indicate the date and time you will teach the lesson/activity.	
Estimated time for lesson/activity:	Provide an estimate of the time needed for the lesson/activity.	
Overview	Provide a short description (2-3 sentences) of the lesson/activity.	C1: Quality of the Learning Goals C3: Quality of the Instruction
Context of lesson	Describe the unit of study, including the lesson that comes before and after your lesson, and explain how these lessons help develop a big idea or disciplinary practice.	
Sources	List the source(s) you used in the creation of your lesson plan—e.g., websites, curriculum materials, books. If you drew heavily on or adapted an existing lesson plan, note that. Please turn in copies of the original lesson plan from the teacher's guide (if relevant) with your assignment.	

Learning Goals and EEE Connection

Section	Description	Main Connection to Instructional Planning Considerations
Learning goals	List the learning goal(s) you have for your students. Use measurable behaviors that can be linked to the assessments. Focus on science content (disciplinary core ideas) <i>and</i> scientific practices. Particularly if you are drawing on the Next Generation Science Standards, you may integrate the core disciplinary ideas and scientific practices into a single learning goal. (The statement may also incorporate a crosscutting concept.)	C1: Quality of the Learning Goals C2: Quality of the Assessments C3: Quality of the Instruction
Connections to standards	State the content expectations from the Michigan GLCE(s), Next Generation Science Standards, Common Core State Standards [with specific connection to science]. You may also want to state the standard(s) from your local curriculum that you address in your lesson, but please be sure you also include the state or national standard you are working toward.	
Type of Assessment	Name the type of assessment you will use to assess student learning (e.g., worksheet, exit slip, teacher observation, whole class discussion). Make clear how it connects to the learning goal(s). Remember, the last dimension of the <i>Explain</i> element of the EEE framework entails applying knowledge to new problems or questions. This provides an excellent context for assessment.	
Connection to activities	Briefly describe how the activities in the instructional sequence help students make progress toward the stated learning goal(s).	
Investigation question	Write out the specific investigation question driving the lesson. This question should establish a meaningful purpose for experiencing the scientific phenomenon and should generate interest among the students.	
Claim with evidence and reasoning	Write out the claim (possibly two claims) that you hope students will generate. Identify the evidence from this lesson (and any relevant previous lessons) that students will use to support the claim. Identify the reasoning (scientific idea or principle) that students can use to support the claim and connect the claim to the evidence. Even if students are not providing the reasoning component as a part of your lesson, you need to articulate the big scientific idea or principle that applies.	

Attending to the Learners

Section	Description	Main Connection to Instructional Planning Considerations
Anticipating student ideas	<p>Explain what you think will be students' <u>prior knowledge</u> about the content, including the alternative ideas or challenges you anticipate students might face and how you plan to work with each of these challenges during the lesson. Also explain your ideas about how students are likely to respond to the tasks in the lesson and how you might use these <u>likely responses</u> to focus students on the intended content.</p> <p>Draw on resources such as the MSTA list, Benchmarks chapter 15, or resources found on CTools. <u>Connect back to specific readings or sources.</u></p> <p>Here, you may also want to anticipate inaccurate or inappropriate claims or evidence students may generate.</p>	<p>C3: Quality of the Instruction</p> <p>C4: Learners in My Classroom</p>
Making the content accessible to all students	<p>Describe how you will help ALL students engage productively in the lesson. This includes identifying assumptions made during the lesson about students' prior experiences, knowledge, and capabilities; making the representations, explanations, and/or vocabulary accessible and meaningful to all students; and making connections to students' personal, cultural, and social experiences during the lesson, if appropriate.</p> <p>Consider how you will use the leverage points for promoting equitable science instruction we've worked on:</p> <ul style="list-style-type: none"> • selecting and supporting science experiences and contexts with care • introducing and using scientific language carefully • making scientific practices and content explicit • supporting meaningful participation by all students 	<p>C4: Learners in My Classroom</p>

Instructional Sequence

Section	Description	Main Connection to Instructional Planning Considerations
Materials	<p>List the materials you will need and the materials the students will need. Include quantities and indicate which are attached. <u>Be sure you have tried your science investigation using the materials you will have at school.</u></p> <p><u>Attach all documents that you plan to use in your lesson</u>, including overheads, assessments, rubrics/answer keys, worksheets, and handouts. (In creating your handouts, be sure you think carefully about the specific questions you're giving students as well as the format for them to write any responses. For example, is there enough room for children's large writing? Are the page breaks in the right spots? Are the instructions clear and kid-friendly? Is everything spelled correctly and grammatically correct? Do the artifacts look professional?)</p>	

Time	<p>Structure your lesson/activity into chunks or segments in order to break it down into its component parts, and then list the time it will take to complete each part. You may even want to add an additional column to indicate larger chunks of instruction.</p> <p>Be specific about what you will do and how long each activity will take. Try to envision each main element of the lesson and make a realistic estimate of how long it will take—remember to account for distributing materials, confusion about setting up the investigation, etc. Consider what portion(s) of the lesson would you shorten or eliminate, if things are running longer than you'd expected. The biggest problem novice science teachers face is running out of time for the sensemaking about the activity or investigation (the <i>Explain</i> element).</p>	C3: Quality of the Instruction
Steps describing what the teacher and students will do	<p>Describe the activities that you will do with your students. Communicate HOW, not just WHAT, you plan on teaching, and provide enough specificity that someone else could teach from your plan. This includes scripting the key questions you plan to ask. Identify at least 5 questions to use at specific points throughout the lesson that will foster students' scientific sense-making.</p> <p>The first element of your instructional sequence (ENGAGE) should detail how you will launch the lesson. This will include engaging students in the following tasks (as appropriate):</p> <ul style="list-style-type: none"> • Posing a focal question/problem to establish a meaningful purpose for the lesson. • Sharing initial ideas about the focal question. • Potentially: Participating in an initial shared experience. <p>The second element of your instructional sequence (EXPERIENCE) should detail how you will engage students in setting up and carrying out an</p>	<p>C3: Quality of the Instruction</p> <p>C4: Learners in My Classroom</p>

	<p>investigation. This will include engaging students in the following tasks (as appropriate):</p> <ul style="list-style-type: none"> • Establishing data collection protocols. • Carrying out the investigation. <p>The third element of your instructional sequence (EXPLAIN) should detail how you will promote students' sense-making. This will include engaging students in the following tasks (as appropriate):</p> <ul style="list-style-type: none"> • Identify patterns and trends in the data for answering the investigation question or problem • Generate claims supported by scientific evidence and reasoning. (Write out the claims with evidence and reasoning that you hope students will generate.) • Applying knowledge to new situations. <p>For each of the elements, specify what you will be expecting to observe as the students engage in the lesson and in what format they will be engaging. The format is the number of students who will be working together on a particular task such as whole class, small group (specify how many), or as individuals. You will want to specify any observable behaviors that you will to see and hear.</p>	
Notes and reminders, including management considerations	<p>Include additional things that you want to remember to do during instruction. This includes management considerations (e.g., how you will manage the distribution and clean up of materials, transitions between segments of instruction, group work (if relevant), and students who finish early from a task.)</p>	C5: Classroom Management and Norms

Reflection on Planning

Section	Description
Learning goal for self	State at least one learning goal that you have for yourself, with regard to your teaching. In other words, what are you working on to improve your teaching practice? If someone will be observing your lesson, also think about what aspect of your teaching you would like the observer to focus on. This may or may not be the same thing as the learning goals you have for yourself.
Preparing to teach this lesson	Describe the things you did in preparation to teach this lesson. For example: practiced the activity with the actual materials, answered the worksheet questions myself, thought through timing, researched materials, etc.

Instructional Planning Considerations

Consideration 1. Quality of Learning Goals

- a. Are the learning goals **well-specified**? (Do they specify what students should know, understand, and/or be able to do as a result of engaging in the lesson¹⁴?)
- b. Do the learning goals focus on **worthwhile content**¹⁵? (Are the learning goals important to learning the discipline; aligned with standards; useful in school, in life, and/or on the test?)
- c. Does the lesson **connect** in a sensible **sequence** to other lessons within the unit, to develop a **coherent** storyline?

Consideration 2. Quality of Assessments

- a. Are the assessments **aligned** with the main learning goals (including concepts, practices, and skills)?
- b. Do the formative assessments enable the students and the teacher to **monitor progress** toward the learning goals?
- c. Do the assessments provide **all students** the opportunity to show what they know, understand, and/or are able to do as a result of engaging in the instruction?

Consideration 3. Quality of the Instruction

- a. Does the lesson provide high-quality opportunities for students to **participate with, reason about, and make sense of the content**?
- b. Do the **representations of content** (i.e., explanations, illustrations, and analogies) support students' understandings of the concepts, practices and skills?
- c. Are there opportunities for students to **share their ideas** throughout the lesson?
- d. Are there opportunities for students to make **connections** among learning goals, activities, tasks, and ideas, within and across lessons?

Consideration 4. Learners in My Classroom

- a. Does the lesson provide opportunities to **differentiate** instruction to ensure equitable access to learning for all of my students?
- b. Does the lesson demonstrate an awareness of and appreciation for cultural differences and social diversity, draw on diversity as a resource in instruction, and help my students make meaningful **connections** between the content and their own lives?
- c. Does the lesson make appropriate **assumptions** about prerequisite knowledge and skills, including knowledge of the concepts and vocabulary? Does the lesson communicate these assumptions and help me prepare my students so that they have equitable access to the learning opportunities?

¹⁴ Although the word "lesson" is used throughout the document, these considerations can also be applied to smaller tasks, larger units as well as other types of resources.

¹⁵ "Content" throughout the document refers to concepts, procedures, ideas, and facts, as well as disciplinary practices (such as making predictions in science or constructing mathematical arguments in mathematics).

Consideration 5. Classroom Management and Norms

- a. Is the **timing** and pacing appropriate?
- b. Is the distribution, use and collection of **materials** well-managed?
- c. Are **participation structures** for students (e.g., whole group, small group, partner, individual) appropriate to the learning goals?

Appendix B: Post Elementary Science Methods Course Interview

1. In the elementary science methods course, you planned and taught a variety of science lessons. As a reminder, these included your peer teaching lesson about _____, your Small Scale Science Teaching lesson, and your Full Scale Science Teaching lesson.
 - a. In general, what resources did you draw on to plan your science lessons? Why did you use those resources?
 - b. What did you look for when making decisions about the strengths and weaknesses of science lessons? Why did you look for those things?
2. During the elementary science methods course, we structured science lessons using the Engage, Experience, and Explain (EEE) framework. Thinking about either your peer teaching lesson or your full scale science teaching lesson, what were your objectives for the *Engage* segment of the science lesson?
 - a. Can you walk me through how you taught the *Engage* segment of your [peer teaching or full scale science teaching] lesson?
3. What were your objectives for the *Experience* segment of your [peer teaching or full scale science teaching] lesson? What participation structures did you use?
 - a. Can you walk me through how you taught the *Experience* segment of your [peer teaching or full scale science teaching] lesson?
4. What were your objectives for the *Explain* segment of your [peer teaching or full scale science teaching] lesson?

- a. Can you walk me through how you taught the *Explain* segment of your [peer teaching or full scale science teaching] lesson?
- 5. The next set of questions asks about your thoughts on the science knowledge that an elementary teacher needs to teach science.
 - a. Did you feel confident to teach [science topic] for your Full Scale Science Teaching lesson?
 - i. What made that lesson an investigation?
 - b. [Show intern list of science practices from the NGSS.] In the science methods class, we talked quite a bit about the science practices, with particular emphasis on scientific explanation. Why do you think it is important for students to engage in the science practices?
 - c. What were the main science practice or practices you focused on in your Full Scale Science Teaching lesson?
 - i. How did you support your students in engaging in those science practices?
 - d. Thinking back to the science lessons you taught, how comfortable were you with engaging students in making claims supported by evidence?
 - e. In the science methods class we talked some about representations, which could be models, diagrams, concept maps, pictures, equations, among others. Did you use any representations during your Full Scale Science Teaching lesson and if so, how?
 - f. How comfortable were you in responding to students' alternative ideas? What challenges did you face? Why?

6. During peer teaching you received feedback from a group of colleagues and a teacher educator, and you also observed and discussed your colleagues' peer teaching lessons.

I'm interested in what that experience was like for you.

- a. Did you feel comfortable receiving and discussing feedback from your colleagues on your own teaching? Was it helpful for you?
 - b. Did you feel comfortable receiving and discussing feedback from a teacher educator on your own teaching? Was it helpful for you?
 - c. Did you incorporate any suggestions from that feedback on your peer teaching into your Small Scale Science Teaching lesson and/or your Full Scale Science Teaching lesson? Can you give an example of modifications that you made to either or both of those lessons based on the feedback?
7. In the elementary science methods class we also worked on understanding and using the equity leverage points. The following questions ask about your thoughts on these.
- a. What does *selecting and supporting science experiences and contexts with care* mean to you?
 - b. What does *introducing and using scientific language carefully* mean to you?
 - c. What does *making scientific practices and content explicit* mean to you?
 - d. What does *supporting meaningful participation by all students* mean to you?
8. The last few questions ask about your growth as a teacher and learner within the teacher education program.
- a. Imagine two of your friends are debating the purpose of education. They ask you (because you are in education) what you think.

- i. How do you respond? (Probe if necessary: Imagine that one friend says that the purpose of education is to correct kids' ideas so they know the right things and can be well-informed adults." The other friend says, "The purpose of education is to give kids the space to share their ideas so they are active participants in their learning." What would you say in response to these two ideas?)
 - ii. How has your view changed (or not) since entering the teacher education program?
 - b. During the teacher education program, was there a pivotal moment or experience that shaped your thinking about the purpose of education?
9. Can you tell me about how your student teaching experience is going? Are you teaching science? To what extent?

Appendix C: Post Student Teaching Interview Protocol

1. During student teaching, about how often did you teach science?
 - a. Does your mentor teacher often teach science? What does a typical science lesson look like in your classroom?
2. When you did teach science, what resources did you draw on to plan your science lessons? Why did you use those resources?
 - a. What did you look for when making decisions about the strengths and weaknesses of the resources you used? Why did you look for those things?
 - b. How did you structure your science lessons? Did you use any resources from the science methods course or the teacher education program to inform your planning?
3. Thinking back to the science lesson(s) you taught, what were your objectives for the lesson(s)? What assessments did you use? Do you feel the students reached the objectives you had? What makes you think that?
 - a. What science practices did you emphasize during the lesson?
 - b. I noticed that you had students construct scientific explanations? How do you feel that went? OR Can you tell me what you did to support students in their sensemaking?
 - i. What did you try to accomplish in your discussions in your science lessons? How did these go?

- c. I noticed that you used scientific language with your students, like "explanation", "claim", or "evidence." How did that go? OR Can you tell me how you supported your students in using evidence from the investigation/activity/demonstration?
 - d. Can you talk about how you elicited students' thinking
 - e. I noticed that you had students work in small groups to do science investigations. How did this go? How did you support them in being successful? OR How did the whole group investigation/activity/demonstration go? Can you talk about your choice for using a whole group structure instead of small groups?
 - f. How did teaching this lesson inform how you taught other science lessons later in the unit?
 - g. *Ask any other questions specific to this interns' lesson. Follow up on any representations that I noticed in their science lessons.
4. What do you feel are your strengths as a science teacher? What do you feel you still need to work on?
5. The next set of questions asks about your thoughts on the science knowledge that an elementary teacher needs to teach science.
- a. Think back to the science lesson I observed/a science lesson (or unit) you taught during student teaching. If you had to describe this to a third party, how would you describe the big content idea(s) in that lesson/unit?
 - i. Did you feel confident to teach [science topic] during your student teaching?
 - b. [Show intern list of science practices from the NGSS.] In the science methods class, we talked quite a bit about the science practices, with particular emphasis

on scientific explanations. Why do you think it is important for students to engage in the science practices?

- c. In the science methods class we talked some about representations, which could be diagrams, concept maps, pictures, equations, among others. Did you use any representations during student teaching and if so, how?
 - d. How comfortable were you in responding to students' alternative ideas? What challenges did you face? Why?
6. In the elementary science methods class, we also worked on understanding and using the equity leverage points. I realized that you may not have been explicitly thinking about these, but could you tell me how you tried to provide an equitable science learning experience for all your students?
- a. (Probe: How intern used each ELP: (a) *selecting and supporting science experiences and contexts with care*, (b) *introducing and using scientific language carefully*, (c) *making scientific practices and content explicit*, and (d) *supporting meaningful participation by all students*.)
7. The last few questions ask about your growth as a teacher and learner within the teacher education program.
- a. Imagine two of your friends are debating the purpose of education. They ask you (because you are in education) what you think.
 - i. How do you respond? (Probe if necessary: Imagine that one friend says that the purpose of education is to correct kids' ideas so they know the right things and can be well-informed adults." The other friend says, "The purpose of education is to give kids the space to share their ideas so they

are active participants in their learning." What would you say in response to these two ideas?)

ii. How has your view changed (or not) since entering the teacher education program?

b. During the teacher education program, was there a pivotal moment or experience that shaped your thinking about the purpose of education?

i. Science teaching or teaching more generally?

8. What are you most excited about with regard to becoming a teacher? With regard to teaching science, specifically?

9. Is there anything else you want to share?

Appendix D: Sample First Year Teaching Interview Protocol

1. (These questions are customized for each novice teacher based on the videorecords of their science teaching.) The first set of questions asks about your thoughts on the science knowledge that you have drawn upon while teaching. I am going to play three short segments of video from your lesson that you recently taught and then ask a few questions about each one. While watching these videos, try putting yourself back in the moment of teaching and focus on what you were thinking while doing so.
 - a. Play video clip of teacher using some form of a representation (e.g., representation of data; representation of science concepts).
 - i. Can you talk about why you chose this representation/to represent the data in this way? Did you plan to use this representation or not?
 - ii. Do you feel it helped the students understand the science ideas better? Are there any parts of the science ideas and/or science practices that are still invisible to the students even after using this representation?
 - iii. What would you change if you were in that moment again, if anything?
 - b. Play video clip of teacher using both scientific language and common language related to the content or science practices.
 - i. Can you talk about the language you were using here?
 - ii. Why did you choose to use that language with your students?
 - iii. How do you feel the language supported or did not support the students in understanding the science ideas and/or science practices?

- c. OR Play a video clip of a teacher when s/he brings up a real-world example or a student brings up a real-world example.
 - i. Can you talk about how that real-world example connects to the science ideas in the lesson?
 - ii. Why did you choose to use that real-world example? OR If you were in that moment again, would you respond the same way or not to the student? How would you change how you responded, if you chose to do so?
 - iii. Do you feel the real-world example supported all students' understanding of the science ideas? Was there any language that you thought was challenging for your students? Why?
 - d. Play video of the sensemaking discussion, allowing the intern to stop the video at various points, if they choose. If not, then I will draw their attention to an interaction they had with one or more students about the students' ideas.
 - i. Can you talk about what you were thinking when this student gave their comment?
 - ii. If you were in that moment again, how would you restate his/her idea(s) for the other students in the class?
 - iii. How comfortable are you in responding to students' alternative science ideas? What challenges do you face? Why?
 - e. The Next Generation Science Standards emphasize the science practices. Why do you think it is important for students to engage in the science practices?
2. Thinking back to the science unit that the lesson we watched came from, what were your objectives for the unit?

- a. What science practices did you emphasize during the lessons/unit?
 - b. Can you tell me what you did to support students in their sensemaking?
 - c. Do you use scientific language with your students, like "explanation", "claim", or "evidence"? How did that go?
 - d. How do you elicit students' thinking?
 - e. What do you try to accomplish in your discussions in your science lessons? How do these go?
3. Science teaching also involves providing equitable opportunities for all students. I realize that you may not be explicitly thinking about these, but could you tell me how you tried to provide an equitable science learning experience for all of your students?
 - a. (Probe: How beginning teacher used each ELP: (a) *selecting and supporting science experiences and contexts with care*, (b) *introducing and using scientific language carefully*, (c) *making scientific practices and content explicit*, and (d) *supporting meaningful participation by all students*.)
4. What main goal(s) do you have for yourself as a teacher and learner? Science teacher and learner?
5. How can we, as science teacher educators, continue to support you during this demanding first year of teaching?
6. Is there anything else you want to share?

Appendix E: Sample Second Year Teaching Interview Protocol

1. Thinking back to the science unit that you taught (or are teaching), what were/are your objectives for the unit?
2. (These questions are customized for each novice teacher based on the videorecords of their science teaching. Video clips and questions are only asked if they are present in the teachers' video. Typically 3-4 video clips are played depending on what is present in the video.) The first set of questions asks about your thoughts on the science knowledge that you have drawn upon while teaching. I am going to play short segments of video from your lesson that you recently taught and then ask a few questions about each one. While watching these videos, try putting yourself back in the moment of teaching and focus on what you were thinking while doing so.
 - a. Play video clip of teacher using some form of a representation (e.g., representation of data; representation of science concepts).
 - i. Can you talk about why you chose this representation/to represent the data in this way? Did you plan to use this representation or not?
 - ii. Do you feel it helped the students understand the science ideas better? Are there any parts of the science ideas and/or science practices that are still invisible to the students even after using this representation?
 - iii. What would you change if you were in that moment again, if anything?
 - b. Play video clip of teacher using both scientific language and common language related to the content or science practices.

- i. Can you talk about the language you were using here?
 - ii. Why did you choose to use that language with your students?
 - iii. How do you feel the language supported or did not support the students in understanding the science ideas and/or science practices?
- c. Play a video clip of a teacher when s/he brings up a real-world example or a student brings up a real-world example.
 - i. Can you talk about how that real-world example connects to the science ideas in the lesson?
 - ii. Why did you choose to use that real-world example? OR If you were in that moment again, would you respond the same way or not to the student? How would you change how you responded, if you chose to do so?
 - iii. Do you feel the real-world example supported all students' understanding of the science ideas? Was there any language that you thought was challenging for your students? Why?
- d. Play video of the sensemaking discussion, allowing the intern to stop the video at various points, if they choose. If not, then I will draw their attention to an interaction they had with one or more students about the students' ideas.
 - i. Can you talk about what you were thinking when this student gave their comment?
 - ii. If you were in that moment again, how would you restate his/her idea(s) for the other students in the class?

- e. Did you feel confident that you knew the science topic [insert topic] well enough to teach it? [If they say yes, ask why and maybe about a time they did not feel comfortable.]
 - i. If not, what did you do to increase your own knowledge?
- 3. The next set of questions asks about your experiences teaching science more broadly.
 - a. How comfortable are you in responding to students' alternative science ideas?
What challenges do you face? Why?
 - b. The Next Generation Science Standards emphasize the science practices. What do you think students learn from engaging in the science practices?
 - c. What science practices did you emphasize during the lessons/unit so far? How did they go?
 - d. Can you tell me what you did to support students in their sensemaking?
 - e. Do you use scientific language with your students, like "explanation", "claim", or "evidence"? How did that go?
- 4. Within the current science unit you are teaching, what do you feel are your strengths or that you feel you have strong knowledge about for teaching this unit? What do you feel you still need to know/work on?
- 5. What main goal(s) do you have for yourself as a teacher and learner? Science teacher and learner?
- 6. How can I, as science teacher educators, continue to support you during your second year of teaching?
- 7. Is there anything else you want to share?

Appendix F: Sample Second Year Teaching Context Interview Protocol

The purpose of this interview is to learn about your science teaching, views of science, and school context more broadly. The first few questions ask about your science teaching throughout the year.

1. How often did you teach science this year?
 - a. What were your big picture goals when teaching science this year?
2. Can you tell me what you did to support students in their scientific sensemaking?
3. As you know, the NGSS advocates for engaging students in the science practices. What do you think students learned from engaging in the science practices?
 - a. Claudia: In your survey, you said that you did not feel confident in your knowledge of students' alternative ideas, challenges, and experiences with science practices and how students learn about the science practices across grades. Can you talk about why you feel this way? Ask this question to Harry and Diana
4. Throughout your teaching how would you determine whether you needed to learn more about the science concepts you were teaching?
5. What do you feel is the value of science as compared to other subject areas?
 - a. If have time: What (if anything) do you think is the benefit for students to learn science?
 - b. If have time: What strengths do you think children bring to the learning of science?

The next set of questions ask about potential resources, such as curriculum materials, physical materials, and others, in your school and how they may have supported your science teaching.

6. Thinking back to your science teaching this year, what resources were most helpful for you in your science teaching? What resources did you wish you had to support your science teaching?
7. How supportive were the curriculum materials for your science teaching? For your learning about science and science teaching?
 - a. No Curriculum Materials (Diana): For the other science units you taught without curriculum materials, what did you use to support your science planning and instruction? How supportive were those resources for your teaching and learning about science and science teaching?
 - b. Curriculum Materials: How would you decide what you would use or not use from the curriculum materials?

The next set of questions asks about potential opportunities and support from others in your school and beyond for your science teaching.

8. How has the school context affected your science teaching this year?
 - a. What was most helpful?
 - b. What was least helpful?
9. Did you ever plan with or talk with other teachers in your school about your science teaching?
 - a. Claudia: The other day, you mentioned getting guidance from a science committee for using a KLEWS chart. Was this committee in the school or at the district level and how did they support and/or guide your science teaching?

10. Not for Claudia: Have you had opportunities to participate in professional development about science teaching and learning this year?
- a. Who put them on and what were they about?
 - b. How did they help you learn about science teaching and learning?
11. Have you had any experiences (e.g., professional development) or worked with any resources (e.g., curriculum materials) that were not focused on science teaching, yet helped you in your science teaching? How did they help you in your science teaching?
- a. Claudia: You had mentioned that your students developed Exhibition projects and that many were related to science. Can you talk about what these projects were and how they related to science?
12. How does your principal support science teaching and learning?
- a. If have time: How do you feel your principal views science teaching and learning?
13. How does your district support science teaching and learning?
- a. If have time: How do you feel your district views science teaching and learning?
14. Claudia: You mentioned in your final survey that you do not feel confident in broadening “what counts” as scientific proficiency. Can you talk about why you feel that way?
(modify for Harry and Diana)
15. What do you learn from students and their families about science teaching and learning?
- a. When you would elicit students’ ideas during your science lessons, how would you use those ideas to support your science teaching practice?
16. I’m looking at how you have developed as a science teacher since you started in the teacher education program. How would you describe your development over that time?

(e.g., Claudia – support for scientific language and engagement in practices; Harry – giving kids agency now; Diana – taking up students' ideas)

- a. How would you describe how your knowledge about science and science teaching has developed over time?
 - i. Do you feel more confident in your understanding of how the science content you teach fits in with what your students have previously learned and will learn later in MS and HS? (HCK)
 - ii. How do you feel your understanding of students and their lived experiences in relation to science have developed over time? (KCS)
 - iii. How do you feel your understanding of how science relates to other subjects has developed over time?

17. The last few questions ask about your growth as a teacher and learner within the teacher education program.

- a. Imagine two of your friends are debating the purpose of education. They ask you (because you are in education) what you think.
 - ii. How do you respond? (Probe if necessary: Imagine that one friend says that the purpose of education is to correct kids' ideas so they know the right things and can be well-informed adults." The other friend says, "The purpose of education is to give kids the space to share their ideas so they are active participants in their learning." What would you say in response to these two ideas?)
 - iii. How has your view changed (or not) since entering the teacher education program?

- b. During the teacher education program, was there a pivotal moment or experience that shaped your thinking about the purpose of education?
 - i. Science teaching or teaching more generally?
- 16. What main goal(s) do you have for yourself as a teacher and learner? Science teacher and learner?
- 17. Is there anything else I should know about how science is taught or valued in your school?

Thank you for all that you have done for our work on this project to help us learn more about how new teachers develop their science teaching practices. All that you have shared will help us continue to learn how to better support new teachers as they learn how to teach elementary science. And please keep in touch with myself, Betsy, and Annemarie. We have enjoyed working with you and want to continue to stay connected with you in the coming years. Enjoy the summer and good luck in all that you aim to accomplish!

Appendix G: Sample Teacher Survey

1. Hello! Thank you for taking time complete this survey. The following questions should take you between 5 to 10 minutes to complete. We plan to use this survey to tailor subsequent surveys to your personal situation, so please fill them out to the best of your ability. Thank you again!
 - a. Please include your name below.
2. Did you teach science regularly in the past month?
 - a. Yes
 - b. No
3. Could you elaborate on your personal classroom situation in regards to science teaching? This will help us to tailor this survey more to your experience.
4. In the past month, what unit(s) have you taught or are you currently teaching?
5. In the past month, how often did you do each of the following in your science instruction?

	Never	Once or Twice	Often
Explain science ideas to the whole class	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Engage the whole class in discussions	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Have students work in small groups	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Have students complete worksheets and/or science notebooks	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Conduct a demonstration while students watch	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

6. In the past month, how often did you do each of the following in your science instruction?

	Never	Once or Twice	Often
Do hands-on/laboratory activities	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Have students read from a science text, module, or other science-related material in class, either aloud or to themselves	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Have students make and/or use representations of data and/or science ideas	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Require students to supply evidence in support of their claims	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Focus on literacy skills (e.g., informational reading or writing strategies)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

7. In the past month, to what extent did you do each of the following while teaching your unit(s)?

	Not at all	Somewhat	To a great extent
You used the curriculum to guide the overall structure and content emphasis of the unit	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
You followed the curriculum to guide the detailed structure and content emphasis of the unit	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
You incorporated activities (e.g., projects, investigations, readings) from other sources to supplement what the curriculum was lacking	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

8. During this unit, when you added or skipped activities (e.g., projects, investigations, readings) in the curriculum, to what extent did each of the following guide your decision(s)?

	Not a factor	A minor factor	A major factor
The science ideas addressed in the activities you skipped were not included in your pacing guide, and/or current state standards	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
You did not have the materials needed to implement the activities you skipped	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
The activities you skipped were too difficult for your students	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Your students already knew the science ideas or were able to learn them without the activities you skipped	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
You had different activities for those science ideas that work better than the ones you skipped	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Supplemental activities were needed to support students at different levels of achievement in order to increase their understanding of the ideas targeted in each activity	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

9. How well prepared do you feel to do each of the following as part of your instruction?

	Not adequately prepared	Somewhat prepared	Fairly well prepared	Very well prepared
Anticipate difficulties that students may have with particular science ideas and practices	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Find out what students think or already know about key science ideas	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Implement the science curriculum materials I have	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Monitor student understanding	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Assess student understanding	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

10. Is there anything else you would like to share with us?

11. Thank you for completing the survey! We appreciate your response.

Appendix H: Mentor Teacher Interview Protocol

Goal: 15 minute interview

Purpose: Characterize school context with regard to science teaching.

1. Roughly how often do you teach science?
2. What does your typical science lesson look like? What are your typical big-picture goals for a science lesson or unit? (*probe for activity-driven or driven by sensemaking; see if there's any mention of science practice*)
3. What resources or materials do you typically draw on in your science teaching? (*probe for some description*) Do you have science curriculum materials and science supplies available to you in your classroom?
 - a. We're interested in how access to resources helps you teach science, or might preclude you from teaching science or from teaching it in the way you'd prefer. Are there any other kinds of resources around your school that help you teach science, or, that you would need? (*probe for, e.g., science supply room, sinks, natural area*)

- b. Do you ever work with other teachers (or coaches, your principal, or others at the district level) on science teaching?
- 4. What do you feel is the value of science as compared to other subject areas?
 - a. What (if anything) do you think is the benefit for students to learn science?
 - b. How might teaching science support your other goals (such as your language arts or math goals)?
 - c. We're also interested in how the value is seen in the school or district. How do you think your principal or district-level administrators see the value of science in comparison to other subject areas? (*probes: Are you encouraged to teach science? Do you ever get science-specific opportunities for professional development?*)
- 5. What strengths do you think children bring to the learning of science?
- 6. Is there anything else I should know about how science is taught or valued in your school?

Appendix I: Principal Interview Protocol

Goal: 15 minute interview

Purpose: Characterize school context with regard to science teaching.

1. Roughly how often do you teach science?
2. What does your typical science lesson look like? What are your typical big-picture goals for a science lesson or unit? *(probe for activity-driven or driven by sensemaking; see if there's any mention of science practice)*
3. What resources or materials do you typically draw on in your science teaching? *(probe for some description)* Do you have science curriculum materials and science supplies available to you in your classroom?
 - a. We're interested in how access to resources helps you teach science, or might preclude you from teaching science or from teaching it in the way you'd prefer. Are there any other kinds of resources around your school that help you teach science, or, that you would need? *(probe for, e.g., science supply room, sinks, natural area)*
 - b. Do you ever work with other teachers (or coaches, your principal, or others at the district level) on science teaching?
4. What do you feel is the value of science as compared to other subject areas?
 - a. What (if anything) do you think is the benefit for students to learn science?
 - b. How might teaching science support your other goals (such as your language arts or math goals)?

- c. We're also interested in how the value is seen in the school or district. How do you think your principal or district-level administrators see the value of science in comparison to other subject areas? (*probes: Are you encouraged to teach science? Do you ever get science-specific opportunities for professional development?*)
- 5. What strengths do you think children bring to the learning of science?
- 6. Is there anything else I should know about how science is taught or valued in your school?

Appendix J: Rubric for Coding Quality of Teachers' Knowledge of Scientific Investigations

Sub-Domain	Knowledge	Does not meet (1)	Approaches (2)	Meets (3)	Exceeds (4)
Core content knowledge (CCK)	The teacher knows that investigations may involve using variables possibly a control	The teacher does not tell students that investigations involve variables and controls	The teacher tells students that they are conducting an investigation that involves using variables and a control (if applies), but they do not explain what either of those are	The teacher tells students that they are conducting an investigation that involves using variables and a control and they explain what variables or a control are (but not both)	The teacher tells students that an investigation involves using variables and controls and explains what both are
	The teacher knows that investigations involve systematically collecting data	The teacher does not tell students they will conduct an investigation	The teacher tells students they are going to conduct an investigation or that they will test their predictions, but does not tell students that it involves collecting data systematically	The teacher explains the systematic nature of their data collection, but does not connect this to what an investigation is	The teacher explains that investigations involve systematically collecting data in order to have data specific to the investigation and can see patterns
Knowledge of Content	The teacher knows that one way to	The teacher does not explain how	The teacher models or explains how to	The teacher explains how to conduct the	The teacher models how to conduct the

and Teaching (KCT)	support students in conducting an investigation is modeling how to do it, but that modeling should not give away the results The teacher knows that circulating and asking sensemaking questions can help students make connections The teacher knows that students should be the ones conducting the investigation	to conduct the investigation The teacher does not circulate during an investigation The teacher conducted the investigation for the students	conduct the investigation and, in doing so, gives away the results The teacher circulates and asks only procedural questions	investigation without modeling it The teacher circulates and asks both procedural and sensemaking questions	investigation without giving away the results The teacher circulates and asks sensemaking questions The teacher had the students conduct the investigation
Unknown	The teacher engaged students in an investigation, but their knowledge is not visible				

Codebook developed from (Crawford, 2000; Kademian & Davis, in press; Metz, 2011; National Research Council, 2012; Windschitl, 2017; Windschitl et al., 2008)

Rubric for Coding Quality of Teachers' Knowledge of Scientific Predictions

Sub-Domain	Knowledge	Does not meet (1)	Approaches (2)	Meets (3)	Exceeds (4)
Core content knowledge (CCK)	The teacher knows that a prediction should include a justification with the initial ideas	The teacher does not explain what a prediction should include	The teacher explains what a prediction is (e.g., what you think will happen), but does not mention the need for a justification		The teacher explains that a prediction should include a claim with a justification (or reason why)
	The teacher knows that predictions should be revisited based on new data	The teacher does not explain why predictions should be revisited		The teacher explains that predictions should be revisited, but does not explain that the original predictions should not be changed	The teacher explains that predictions should be revisited and not changed
Knowledge of Content and Teaching (KCT)	The teacher knows that students need prompting in order to provide justifications with their predictions	The teacher does not ask students to share their predictions	The teacher asks students to share their predictions, but does not prompt them for a justification with their predictions	The teacher asks students to share their predictions and prompts them for a justification with their predictions	

	The teacher knows that predictions should be recorded	The teacher does not ask students to record their predictions and/or does not record the predictions for the students	The teacher provides space for students to record their predictions or records the predictions for the students, but does not use sentence starters or other supports	The teacher provides space for students to record their predictions or records the predictions for the students and also provides sentence starters or other supports	
	The teacher knows that students need prompting to revisit their predictions	The teacher does not remind students of their original predictions		The teacher reminds students of their original predictions, but does not engage students in comparing them	The teacher reminds students of their original predictions and supports them in comparing their original predictions with the findings of the investigation
	The teacher knows that students should be the ones making predictions	The teacher makes predictions for the students			The teacher had the students make their own predictions
Unknown	The teacher engaged students in making predictions, but their knowledge is not visible				

Codebook developed from (Arias, Bismack, et al., 2016; National Research Council, 2012; Oh, 2010)

Rubric for Coding Quality of Teachers' Knowledge of Scientific Observations

Sub-Domain	Knowledge	Does not meet (1)	Approaches (2)	Meets (3)	Exceeds (4)
Core content knowledge (CCK)	The teacher knows what is necessary to make high-quality observations	The teacher does not explain what should be included in high-quality observations	The teacher explains one thing that should be included in quality observations or that observations should be recorded	The teacher explains two to four things students should include in their observations	The teacher explains that observations should be clear, complete, accurate, objective, and include scientific vocabulary
	The teacher knows that observations are data that can be used as evidence for explanations and arguments	The teacher does not explain that observations will be used as evidence for explanations and arguments		The teacher explains that observations are used to answer investigations questions	The teacher explains that observations will be used as evidence for explanations and arguments
Knowledge of Content and Teaching (KCT)	The teacher knows that one way to support students in making observations is by modeling	The teacher does not model how to make scientific observations	The teacher displays a student's observation or student writes observation on board	The teacher models how to make observations, but is not explicit about what should be included in the observations	The teacher models how to make observations and is explicit about what needs to be included in observations

	The teacher knows that one way to support students in making observations is to provide tools for doing so	The teacher does not provide students with the necessary tools to record accurate observations	The teacher provides students with some tools for recording observations, but does not provide all the needed tools (e.g., only pencil and paper)	The teacher provides students with the necessary tools to make and record accurate observations (e.g., colored pencils, magnifying glasses)
	The teacher knows that many students should share their observations	The teacher does not have students share their observations with a small group or the whole class	The teacher has one or two students share their observations with a small group or whole class	The teacher has more than two students share their observations with a small group or whole class
	The teacher knows that students should be the ones making observations	The teacher made observations for the students		The teacher had the students make their own observations
Unknown	The teacher engaged students in making observations, but their knowledge is not visible			

Codebook developed from (Arias & Davis, 2016; Eberbach & Crowley, 2009; National Research Council, 2012)

Rubric for Coding Quality of Teachers' Knowledge of Analyzing and Interpreting Data

Sub-Domain	Knowledge	Does not meet (1)	Approaches (2)	Meets (3)	Exceeds (4)
Core content knowledge (CCK)	The teacher knows that analyzing and interpreting data involves giving meaning to the data	The teacher does not explain the need to make sense of data in order to answer the investigation question			The teacher explains that the data is only useful if they make sense of it or figure out how they can use it to answer their investigation question
	The teacher knows that tools and representations are used to analyze and interpret data	The teacher does not use a tool or representation to make sense of the data		The teacher uses a tool or representation to make sense of the data, but does not explain the purpose of doing so	The teacher explains that the tool or representation will help students make sense of the data
	The teacher knows that errors can occur when collecting data	The teacher does not identify errors made in the data, when applicable		The teacher identifies errors in individual students' data or small groups' data	The teacher identifies errors across all data and discusses the need to look across the data
	The teacher knows that science knowledge involves gathering consensus about the meaning of multiple sets of data	The teacher does not discuss the role of consensus or articulate the need for gathering consensus	The teacher mentions that science involves consensus but does not explain what this is or only does so for individual data	The teacher gathers consensus of interpretation across groups, but does not explain the role of consensus building for science knowledge	The teacher gathers consensus and discusses the role of consensus building when developing meaning of multiple data sets
Knowledge of Content	The teacher knows that students need prompting to use	The teacher does not probe students	The teacher tells students what the evidence is	The teacher probes students for evidence with their ideas, but is	The teacher probes students for evidence from the investigation

and Teaching (KCT)	evidence from their investigation to support their ideas	for evidence with their ideas		not explicit that the evidence should come from the investigation	that supports their ideas
	The teacher knows that students need prompting in order to identify patterns in the data	The teacher does not ask students what patterns they notice in the data		The teacher asks what patterns the students see in their own data	The teacher asks what patterns the students see in the class data
	The teacher knows ways to use representations as tools to support students in identifying patterns in the data	The teacher does not use a representation when it would be useful	The teacher uses a representation but it does not highlight the patterns in the data	The teacher uses a representation that highlights the patterns in each group's data, but not across groups	The teacher uses a representation that highlights patterns in all of the data
	The teacher knows that students should be the ones identifying patterns in data	The teacher tells the students the pattern(s) in the data			The teacher has students identify the pattern(s) in the data
Unknown	The teacher engaged students in identifying patterns				

in the data, but their
knowledge is not
visible

Codebook developed from (Arias & Davis, 2017a; National Research Council, 2012; Rivet & Ingber, 2017)

Rubric for Coding Quality of Teachers' Knowledge of Scientific Explanations and Arguments

Sub-Domain	Knowledge	Does not meet (1)	Approaches (2)	Meets (3)	Exceeds (4)
Core content knowledge (CCK)	The teacher knows that an explanation and argument includes a claim supported by evidence and reasoning	The teacher does not explain what an explanation and argument is	The teacher explains that an explanation and argument includes a claim, but does not mention evidence and reasoning	The teacher explains that an explanation and argument includes a claim supported by evidence	The teacher explains that an explanation and argument includes a claim supported by evidence and reasoning
	The teacher knows what a claim is	The teacher does not tell students what a claim is	The teacher states the word "claim," but does not discuss what a claim is	The teacher comments on the need to answer the investigation question, but does not call it a claim	The teacher explains that a claim should answer the investigation question
	The teacher knows what evidence is	The teacher does not tell students what evidence is	The teacher asks students for evidence to support the claim, but does not call it evidence	The teacher tells students that evidence should be gathered from the observations	The teacher tells students that evidence should be gathered from the observations and should support the claim
	The teacher knows what reasoning is	The teacher does not tell students what reasoning is	The teacher explains that the reasoning should connect the evidence with the claim, but does not mention the need for a scientific principle	The teacher explains that reasoning should include a scientific principle, but does not mention the need to connect the evidence with the claim	The teacher explains that reasoning should connect the evidence with the claim and include a scientific principle

	The teacher knows that one way to support students in constructing explanations and arguments is to provide them with supports	The teacher does not use sentence starters or any other supports for helping students construct explanations and arguments	The teacher uses supports to help students construct explanations and arguments, but does not explain what should be included in them	The teacher uses supports, such as sentence starters, for helping students construct explanations supported by evidence and reasoning, but does not explain the need for multiple pieces of evidence	The teacher uses supports, such as sentence starters, for helping students construct explanations supported by multiple pieces of evidence and reasoning
Knowledge of Content and Teaching (KCT)	The teacher knows that students should be the ones to construct claims	The teacher constructs the claim themselves			The teacher has students construct their own claims
	The teacher knows that students should gather evidence themselves	The teacher gathers evidence for the students			The teacher has students gather their own evidence
	The teacher knows that students should be the ones developing the reasoning	The teacher develops the reasoning for the students			The teacher had the students develop their own reasoning
Unknown	The teacher engaged students in constructing explanations and arguments, but their				

knowledge is not
visible

Codebook developed from (Arias & Davis, 2017a; McNeill & Krajcik, 2008; National Research Council, 2012)

Rubric for Coding Quality of Teachers' Knowledge of Scientific Modeling

Sub-Domain	Knowledge	Does not meet (1)	Approaches (2)	Meets (3)	Exceeds (4)
	The teacher knows that scientific modeling involves representing the natural world, testing hypotheses to explain phenomena, and predicting potential outcomes based on gathered data from models	The teacher does not explain what scientific modeling is	The teacher explains that scientific modeling involves representing phenomena in the natural world, but does not mention anything about using models to test hypotheses or make predictions	The teacher explains that scientific modeling involves representing phenomena in the natural world and to test hypotheses to explain phenomena, but does not mention using models to make predictions	The teacher explains that scientific modeling involves representing phenomena in the natural world, testing hypotheses to explain phenomena, and making predictions
Core content knowledge (CCK)	The teacher knows that scientific models only represent aspects of the natural world and can never represent all aspects of the natural world	The teacher does not explain that models represent only parts of the natural world	The teacher explains that models only represent physical aspects of the natural world, but does not mention the mechanisms or invisible aspects	The teacher explains that models represent aspects of the natural world (including mechanisms), but does not mention the invisible parts	The teacher explains that models represent particular parts of the natural world (including mechanisms), and that other parts are invisible
	The teacher knows that scientific models should be evaluated and revised based on new data or evidence	The teacher does not explain that models need to be evaluated or revised based	The teacher explains that models should be evaluated based on new data or evidence, but does not explain	The teacher explains that models should be revised based on new data or evidence, but does not explain the need to evaluate	The teacher explains that models should be evaluated and revised based on new data or evidence

		on new data or evidence	the need to revise models	models based on new data or evidence	
	The teacher knows that students should learn to construct scientific models	The teacher constructs scientific models for students	The teacher tells students how to construct scientific model with minimal student input	The teacher tells students how to construct the scientific model (without student input on how to do so), but the students construct the model themselves	The teacher engages students in a discussion of how to construct the scientific model and students construct the model themselves
Knowledge of Content and Teaching (KCT)	The teacher knows that students need to be guided through understanding what aspects of the natural world that a scientific model represents and does not represent	The teacher does not tell students what aspects of the natural world the model represents	The teacher tells students what aspects of the natural world the model represents, but does not include the invisible parts of the model	The teacher engages students in a discussion of what aspects of the natural world the model represents, but does not include what is invisible	The teacher guides students in a discussion of what aspects of the natural world the model represents and what is invisible
	The teacher knows how to supports students in evaluating and revising models based on new data	The teacher does not support students in evaluating and revising models	The teacher evaluates and/or revises the model for the students	The teacher has students evaluate a model based on new data or evidence, but does not revise it	The teacher has students evaluate and revise a model based on new data

	The teacher knows that students need support to use models to explain phenomena	The teacher does not explain the phenomena	The teacher tells students the phenomena without using the model	The teacher uses the model to tell students an explanation of the phenomena	The teacher engages students in a discussion of phenomena using the model to inform the explanation of the phenomena
Unknown	The teacher engaged students in scientific modeling, but their knowledge is not visible				

Codebook developed from (Lehrer & Schauble, 2006; National Research Council, 2012; Passmore et al., 2017; Schwarz et al., 2009; Windschitl et al., 2012)

Appendix K: Interrater Reliability Scores for Coding CKT about Scientific Investigations

Knowledge Sub-Domain	Teachers' knowledge that...	% Positive Agreement	% Negative Agreement*
CKT	Investigations involve using variables and controls	86%	90%
	Investigations involve systematically collecting data	84%	78%
KCT	One way to support students in conducting an investigation is modeling how to do it without giving away the results	82%	--
	Circulating and questioning can help students make connections	78%	78%
	Students should be the ones conducting the investigation	100%	--

*Two dimensions do not have a score for % negative agreement due to few instances of the segments not coded as those dimensions

Interrater Reliability Scores for Coding CKT about Scientific Predictions

Knowledge Sub-Domain	Teachers' knowledge that...	% Positive Agreement	% Negative Agreement*
CKT	Predictions include a justification with initial ideas	90%	93%
	Predictions should be revisited based on new data	86%	89%
KCT	Students need prompting in order to provide justifications with their predictions	90%	--
	Predictions should be recorded	100%	83%
	Students need prompting to revisit their predictions	86%	83%
	Students should be the ones making predictions	100%	--

* Two dimensions do not have a score for % negative agreement due to few instances of the segments not coded as those dimensions

Interrater Reliability Scores for Coding CKT about Scientific Observations

Knowledge Sub-Domain	Teachers' knowledge that...	% Positive Agreement	% Negative Agreement*
CKT	Observations should be clear, complete, accurate, objective, and include scientific vocabulary	84%	73%
	Observations are data that can be used as evidence for explanations and arguments	100%	96%
KCT	One way to support students in making observations is by modeling	92%	74%
	One way to support students in making observations is to provide tools for doing so	97%	73%
	Students should share their observations	79%	--
	Students should be the ones making observations	100%	--

* Two dimensions do not have a score for % negative agreement due to few instances of the segments not coded as those dimensions

Interrater Reliability Scores for Coding CKT about Analyzing and Interpreting Data

Knowledge Sub-Domain	Teachers' knowledge that...	% Positive Agreement	% Negative Agreement*
CKT	Analyzing and interpreting data involves giving meaning to the data**	--	--
	Tools and representations are used to analyze and interpret data	100%	96%
	Errors can occur when collecting data	90%	85%
	Science knowledge involves gathering consensus about the meaning of multiple sets of data	100%	89%
KCT	Students need prompting to use evidence from their investigation to support their ideas	100%	83%
	Students need prompting in order to identify patterns in the data	100%	94%
	Ways to use representations and tools to support students in identifying patterns in the data	100%	74%
	Students should be the ones analyzing and interpreting data	100%	--

*Two dimensions do not have a score for % negative agreement due to few instances of the segments not coded as those dimensions.

**Few segments were coded as demonstrating this dimension, so the majority of the segments were discussed with a second researcher and discrepancies were resolved through discussion.

Interrater Reliability Scores for Coding CKT about Explanations and Arguments

Knowledge Sub-Domain	Teachers' knowledge that...	% Positive Agreement	% Negative Agreement
CKT	Explanations and arguments include claims supported by evidence and reasoning	100%	100%
	Claim answers an investigation question	100%	70%
	Evidence should be gathered from data and should support the claim	70%	90%
	Reasoning should connect the evidence with the claim and include a scientific principle	100%	92%
KCT	One way to support students in constructing explanations and arguments is to provide them with supports	100%	70%
	Students should be the ones to construct claims	100%	72%
	Students should be the ones to gather evidence	100%	88%
	Students should be the ones developing reasoning	100%	89%

Interrater Reliability Scores for Coding CKT about Scientific Modeling

Knowledge Sub-Domain	Teachers' knowledge that...	% Positive Agreement	% Negative Agreement*
CKT	Scientific modeling involves representing the natural world, testing hypotheses to explain phenomena, and predicting potential outcomes based on gathered data from models	75%	81%
	Scientific models only represent aspects of the natural world and can never represent all aspects of the natural world	72%	87%
	Scientific models should be evaluated and revised based on new data or evidence	100%	100%
KCT	Students should learn to construct scientific models	94%	--
	Students need to be guided through understanding what aspects of the natural world that a scientific model represents and does not represent	73%	--
	Ways to support students in evaluating and revising models based on new data	100%	73%
	Students need support to use models to explain phenomena	96%	70%

* Two dimensions do not have a score for % negative agreement due to few instances of the dimensions not coded

Appendix L: Codebook for Opportunities to Learn Knowledge of Content and Teaching

Opportunities that support teachers' knowledge of how to...	Description
Elicit students' ideas	Learning opportunity that supports the teachers' knowledge of how to elicit students' ideas
Explaining core content and language use	Learning opportunity that supports the teachers' knowledge of how to explain science concepts & practices and to be critical of the language they use during instruction
Use the EEE structure of science lessons	Learning opportunity that supports the teachers' knowledge of how science lessons can be divided into three sections: Engage, Experience, and Explain
Interpret and assess students' ideas	Learning opportunity that supports the teachers' knowledge of how to interpret and evaluate student ideas
Use representations of concepts and practices	Learning opportunity that supports the teachers' knowledge of how to use representations of concepts and/or science practices during science teaching
Use text in science	Learning opportunity that supports the teachers' knowledge of how to use text in science lessons
Use physical materials in science	Learning opportunity that supports the teachers' knowledge of how to manage materials in a science lesson
Engage students in small groups in science	Learning opportunity that supports the teachers' knowledge of how to manage small groups
Lesson plan	Learning opportunity that supports the teachers' knowledge of how to plan for science and organize science instruction (includes all three cycles of teaching [Zemba-Saul et al., 2000])
Reflect on one's science teaching	Learning opportunity that supports the teachers' knowledge of how to reflect on their science teaching (includes all three cycles of teaching [Zemba-Saul et al., 2000])
Engage students in asking scientific questions	Learning opportunity that supports the teachers' knowledge of how to have students ask scientific questions
Engage students in conducting investigations	Learning opportunity that supports the teachers' knowledge of how to support students in conducting scientific investigations

Engage students in making predictions	Learning opportunity that supports the teachers' knowledge of how to support students in constructing scientific predictions
Engage students in making observations	Learning opportunity that supports the teachers' knowledge of how to support students in constructing scientific observations
Engage students in interpreting and analyzing data	Learning opportunity that supports the teachers' knowledge of how to support students in analyzing and interpreting data
Engage students in constructing explanations and arguments	Learning opportunity that supports the teachers' knowledge of how to support students in constructing scientific explanations and arguments
Engage students in constructing scientific models	Learning opportunity that supports the teachers' knowledge of how to support students in scientific modeling
Other	Other learning opportunities that support the teachers' knowledge of content and teaching that are not evident in the other aspects of KCT

Codebook for Opportunities to Learn Knowledge of Content and Students

Opportunities that support teachers' knowledge of...	Description
Students' strengths	Learning opportunity highlighting what students are capable of and what they do or what they know
Students' challenges	Learning opportunity that supports teachers' knowledge of students' alternative ideas and challenges with science topics and practices
Students' experiences	Learning opportunity highlighting what previous experiences students have had with regard to the science concepts or practices
Students' attachment to their ideas	Learning opportunity that highlights how much students are attached to their own ideas
Value of students and all that they bring to the classroom	Learning opportunity that supports teachers' valuing of students' ideas, cultures, genders, races, nationalities, age, etc.
Students' developmentally appropriate ideas and/or abilities	Learning opportunity that supports teachers' knowledge of students' developmentally appropriate ideas or abilities with regard to the science concepts and/or practices
Students' race, cultures, identities, and backgrounds related to science	Learning opportunity that supports teachers' knowledge of the influences of students' cultures, backgrounds, race, gender, nationality, etc. on science teaching and learning
Other	Other learning opportunities that support the teachers' knowledge of content and students that are not evident in the other aspects of KCS

Codebook for Opportunities to Learn Knowledge of Content and Curriculum

Opportunities that support teachers' knowledge of...	Description
Curriculum materials	Learning opportunity that supports the teachers' knowledge of what curriculum materials are and the range or types of curriculum materials (Magnussen et al., 1999; Grossman, 1990)
Quality of curriculum materials	Learning opportunity that supports the teachers' knowledge of the quality of curriculum materials (often poor quality, but sometimes they will mention the strengths of curriculum materials)
Standards	Learning opportunity that supports the teachers' knowledge of standards (Magnussen et al., 1999; Grossman, 1990)
Learning goals and how to evaluate learning goals	Learning opportunity that supports the teachers' knowledge of how to read or evaluate learning goals (not writing them)
Modifying and writing learning goals	Learning opportunity that supports the teachers' knowledge of how to modify or write learning goals
Assessments and evaluating assessments	Learning opportunity that supports the teachers' knowledge of how to read or evaluate assessments (not writing them)
Modifying and writing assessments	Learning opportunity that supports the teachers' knowledge of how to modify or write assessments
Other	Other learning opportunities that support the teachers' knowledge of content and curriculum that are not evident in the other aspects of KCC

Appendix M: Interrater Reliability Scores for Coding Opportunities to Learn KCT

Opportunities to Learn Aspects of Knowledge of how to...	% Positive Agreement	% Negative Agreement
Use EEE Framework for science lessons	100%	100%
elicit students' ideas	90%	99%
Explain core content and language use	100%	96%
Facilitate classroom discourse	78%	97%
Interpret and assess students' ideas	80%	97%
Manage science materials	100%	98%
Organize small groups	90%	98%
Use texts in science	100%	98%
Use representations of concepts and practices	--	100%
Lesson plan	--	99%
Reflect on science teaching	100%	99%
Engage students in <i>scientific questions</i>	100%	100%
Engage students in <i>scientific investigations</i>	75%	98%
Engage students in <i>scientific predictions</i>	75%	98%
Engage students in <i>scientific observations</i>	--	98%
Engage students in <i>analyzing and interpreting data</i>	--	99%
Engage students in <i>scientific explanations and arguments</i>	97%	94%
Engage students in <i>scientific modeling</i>	n/a	100%
Engage in Other aspects	84%	97%

*A few dimensions do not have a score for % positive agreement due to the high scores for % negative agreement and only a few instances of the segments coded as those dimensions

Interrater Reliability Scores for Coding Opportunities to Learn KCS

Opportunities to Learn Aspects of Knowledge of ...	Ranges of % Positive Agreement	Ranges of % Negative Agreement
Students' strengths	89%	99%
Students' challenges	90%	99%
Students' experiences	--	100%
Value of students	--	100%
Students' attachment to their ideas	100%	100%
Developmentally appropriate understandings for students	--	99%
Students' race, cultures, identities, and backgrounds related to science	--	99%
Engage in Other aspects	91%	99%

*A few dimensions do not have a score for % positive agreement due to the high scores for % negative agreement and only a few instances of the segments coded as those dimensions

Interrater Reliability Scores for Coding Opportunities to Learn KCC

Opportunities to Learn Aspects of Knowledge of ...	Ranges of % Positive Agreement	Ranges of % Negative Agreement
Curriculum materials	93%	99%
Quality of curriculum materials	--	100%
Standards	94%	100%
Learning goals and evaluation of learning goals	98%	95%
Modifying and writing learning goals	--	100%
Assessments and evaluation of assessments	96%	100%
Modifying and writing assessments	100%	100%
Engage in Other aspects	91%	99%

*A few dimensions do not have a score for % positive agreement due to the high scores for % negative agreement and only a few instances of the segments coded as those dimensions

Appendix N: Opportunities to Learn Aspects of Knowledge of Content and Teaching

Opportunities to learn general aspects of knowledge of content and teaching (of the total coded opportunities to learn KCT in each experience)

Knowledge of how to...	Y1 CaSM (n=248)	Y1 TwCM (n=88)	Y2 ESM (n=819)	Y2 ST Claudia (n=25)	Y2 ST Diana (n=34)	Y2 ST Harry (n=26)	Y3 Claudia (n=98)	Y3 Diana (n=56)	Y3 Harry (n=114)	Y4 Claudia (n=77)	Y4 Diana (n=73)	Y4 Harry (n=89)
Use EEE Framework	0	0	120	2	1	1	4	2	1	0	0	0
elicit students' ideas	95	8	35	2	2	1	5	3	5	0	1	1
explain content and use language	4	7	71	3	1	4	8	8	23	3	8	6
facilitate classroom discourse	15	6	80	6	5	4	19	5	10	0	6	5
interpret and assess students' ideas	56	0	56	4	1	3	19	10	21	7	5	13
manage science materials	16	3	14	2	1	0	1	0	2	0	0	1
organize small groups	0	0	26	0	0	0	5	5	3	0	1	2
use texts	12	0	4	0	2	0	0	3	1	0	0	0
use representations	4	4	47	2	2	1	11	2	16	8	8	6

lesson plan	14	45	101	2	3	4	5	2	5	8	8	5
reflect	29	2	94	0	0	0	3	0	1	1	1	0
use Other aspects	46	14	139	0	4	4	5	3	5	2	2	3

Opportunities to learn aspects of knowledge of content and teaching related to science practices (of the total coded opportunities to learn KCT in each experience)

Knowledge of how to engage students in...	Y1 CaSM (n=248)	Y1 TwCM (n=88)	Y2 ESM (n=819)	Y2 ST Claudia (n=25)	Y2 ST Diana (n=34)	Y2 ST Harry (n=26)	Y3 Claudia (n=98)	Y3 Diana (n=56)	Y3 Harry (n=114)	Y4 Claudia (n=77)	Y4 Diana (n=73)	Y4 Harry (n=89)
asking scientific questions	1	0	29	0	1	0	4	1	2	0	2	1
scientific investigations	5	0	73	0	2	1	6	2	8	1	0	0
making scientific predictions	0	0	19	0	0	0	2	2	1	1	0	0
making scientific observations	0	0	55	0	2	0	2	10	7	2	0	0
analyzing data	2	0	70	1	0	0	8	2	0	0	0	1
constructing scientific explanations and arguments	2	0	151	1	0	2	4	6	6	2	0	1
scientific modeling	2	0	5	1	2	1	1	0	6	0	5	2

Appendix O: Opportunities to learn aspects of knowledge of content and students (of the total coded opportunities to learn

KCS in each experience)

Knowledge of...	Y1 CaSM (n=173)	Y1 TwCM (n=14)	Y2 ESM (n=349)	Y2 ST Claudia (n=10)	Y2 ST Diana (n=23)	Y2 ST Harry (n=5)	Y3 Claudia (n=41)	Y3 Diana (n=34)	Y3 Harry (n=49)	Y4 Claudia (n=30)	Y4 Diana (n=33)	Y4 Harry (n=31)
students' strengths	59	7	71	2	11	1	16	12	16	6	13	8
students' challenges	116	2	132	4	6	1	19	13	17	17	13	11
students' prior experiences	13	1	32	0	0	4	5	4	9	5	3	4
students' attachment to their ideas	6	0	6	0	0	0	0	0	1	1	0	0
students' developmentally appropriate capabilities and ideas	13	0	7	0	0	0	0	0	0	0	1	0
students' cultures, race, genders, identities, etc.	4	5	35	3	3	0	1	0	5	1	3	4

the value of students	23	6	19	0	3	0	0	2	5	4	3	1
Other aspects	14	2	76	2	7	0	7	4	11	2	2	6

Appendix P: Opportunities to learn aspects of knowledge of content and curriculum (of the total coded opportunities to learn

KCC in each experience)

Knowledge of...	Y1 CaSM (n=39)	Y1 TwCM (n=214)	Y2 ESM (n=334)	Y2 ST Claudia (n=5)	Y2 ST Diana (n=3)	Y2 ST Harry (n=12)	Y3 Claudia (n=25)	Y3 Diana (n=14)	Y3 Harry (n=19)	Y4 Claudia (n=27)	Y4 Diana (n=28)	Y4 Harry (n=15)
standards	1	40	165	0	4	3	8	4	7	8	9	6
curriculum materials	10	27	27	0	1	0	18	8	11	22	13	9
quality of curriculum materials	2	26	35	3	6	0	3	1	4	8	11	5
evaluation of learning goals	2	86	21	1	0	0	0	0	0	0	0	0
how to modify and write learning goals	4	12	11	0	1	0	3	0	2	0	2	0
evaluation of assessments	21	49	53	2	5	0	1	3	3	2	3	3

how to modify and write assessments	0	11	26	1	1	0	4	1	1	1	4	0
Other aspects	4	4	2	0	0	0	1	0	0	2	3	0

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